Pre-Launch and On-Orbit Calibration of Greenhouse Gas Sensors: Lessons Learned from the OCO-GOSAT Collaboration

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The Promise and Challenge for Space-based GHG Measurements

Primary assets of space based GHG measurements:

- Spatial coverage: Observations over both land and ocean
- Temporal resolution and sampling
  - Hourly sampling needed to resolve diurnal cycle and plumes
  - Daily to weekly sampling needed to resolve CO_2 weather
  - Monthly measurements required over multiple years to resolve seasonal and inter-annual variability in CO_2
- Spatial resolution and sampling
  - Sensitivity to point sources scales with area of footprint
  - Small measurement footprints enhance sensitivity to point sources and reduce data losses due to clouds

The primary challenges of space-based GHG measurements:

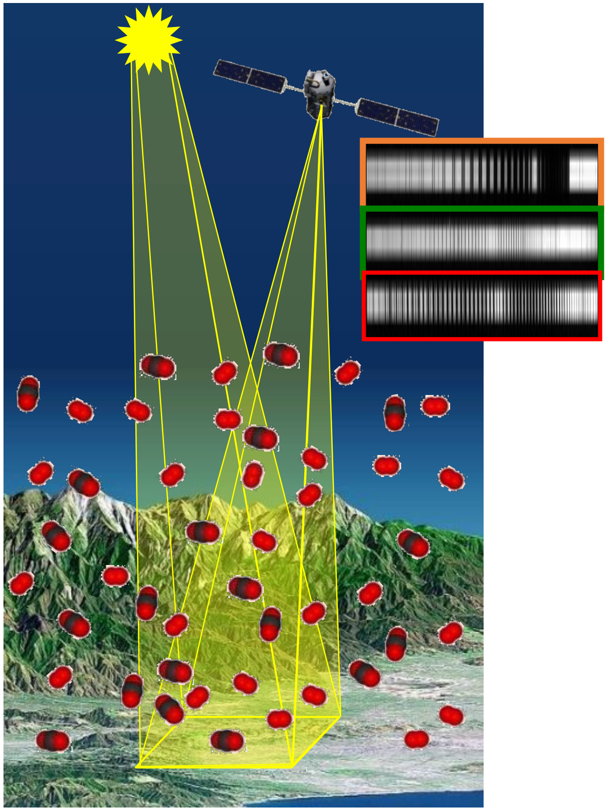
- The need for unprecedented levels of precision and accuracy
  - High precision required to resolve the small (< 0.25%) variations in CO_2 and CH_4 associated with sources and sinks
  - High accuracy essential to yield regional-scale biases < 0.1%

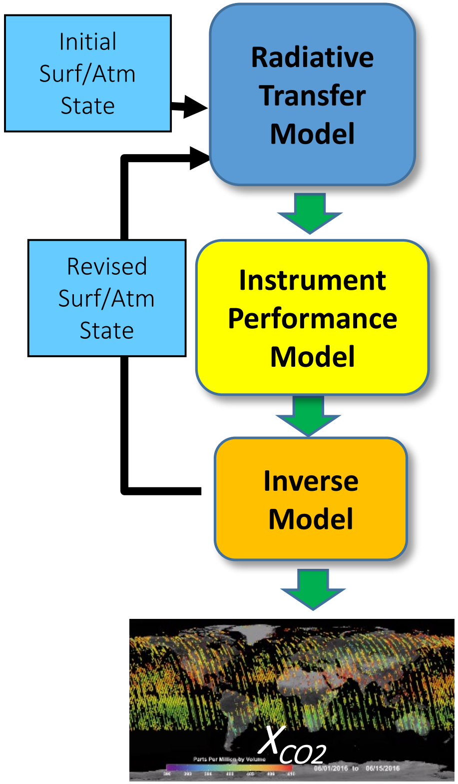
Measuring CO_2 from Space

- **Record** spectra of CO_2 and O_2 absorption in reflected sunlight

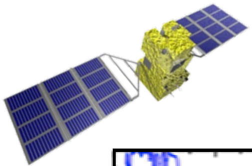
Retrieve variations in the column averaged CO_2 dry air mole fraction, X_{CO2} ov the sunlit hemisphere

Validate measurements to ensure X_{CO2} accuracy of 1 ppm (0.25%)

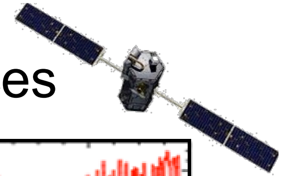


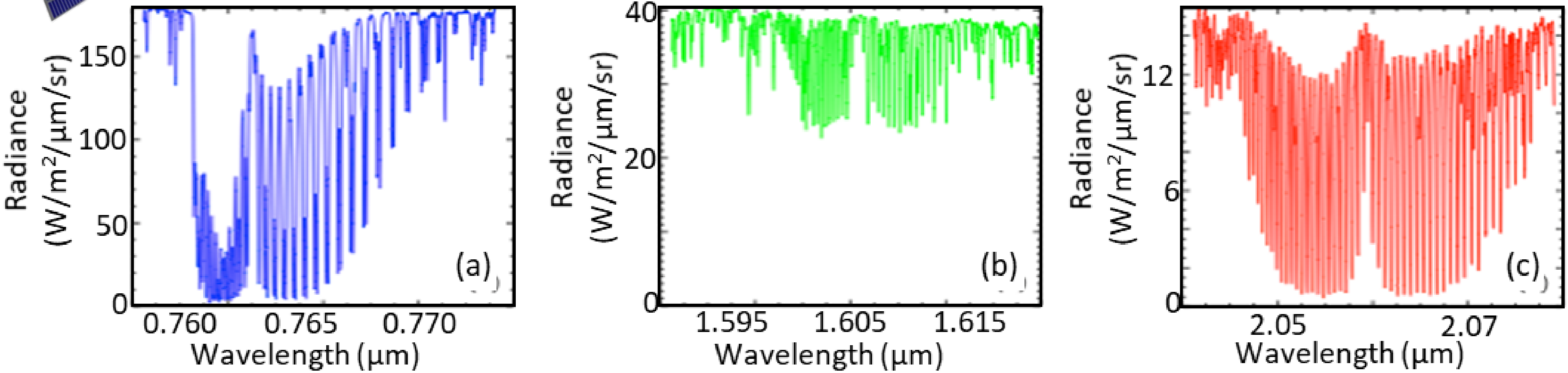


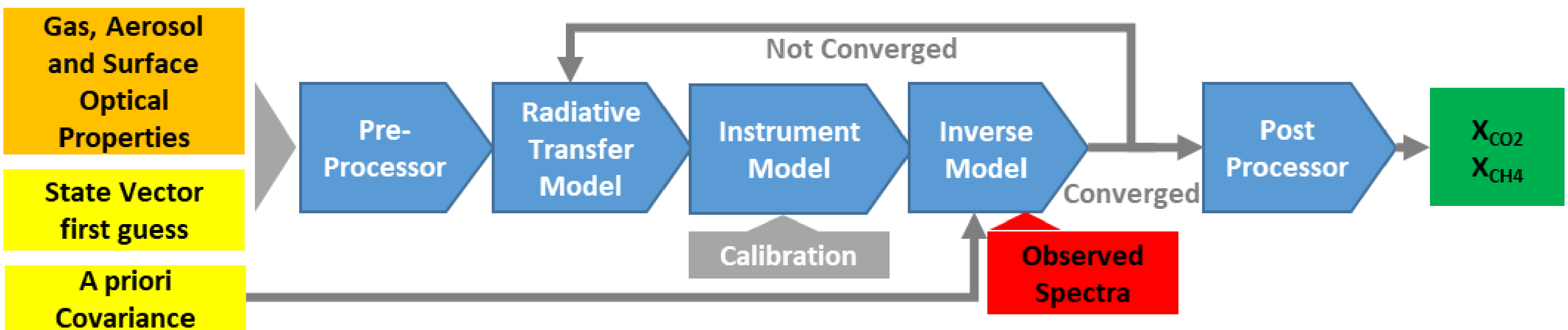
The Primary Data Products



Level 1B: Calibrated, geolocated spectral radiances



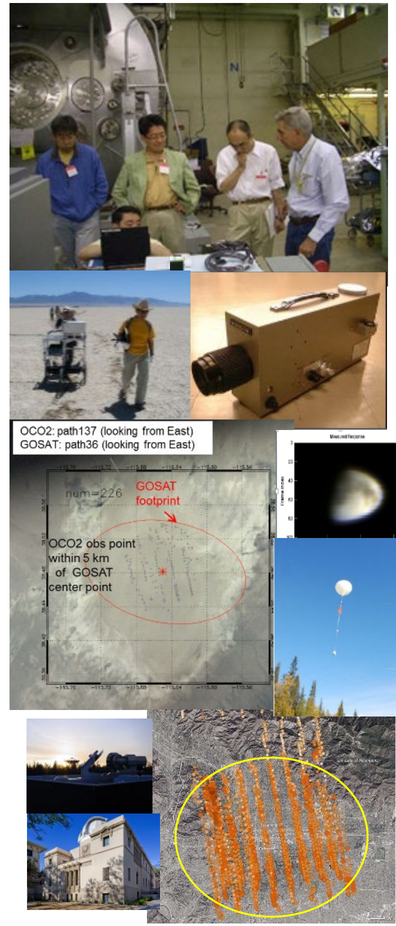




Level 2: Column averaged dry air mole fractions of CO_2 and CH_4

Cross-Calibrating Observations from Greenhouse Gas Missions

- The requirement for high accuracy for greenhouse gas measurements (< 0.1%) imposes stringent constraints on the calibration individual instruments and cross-calibration of data from different instruments
- Lessons learned from the GOSAT, OCO collaboration suggest the following minimum requirements
  - Pre Launch:
    - Exchange information on best practice for pre-launch instrument characterization
    - Cross calibrate pre-launch radiometric standards against internationally-recognized (Si-Traceable) standards
  - Post Launch:
    - Exchange solar and lunar (ROLO) standards and best practices for solar and lunar observations and analysis
    - Conduct joint vicarious calibration campaigns and coordinate observations of pseudo-invariant Earth targets



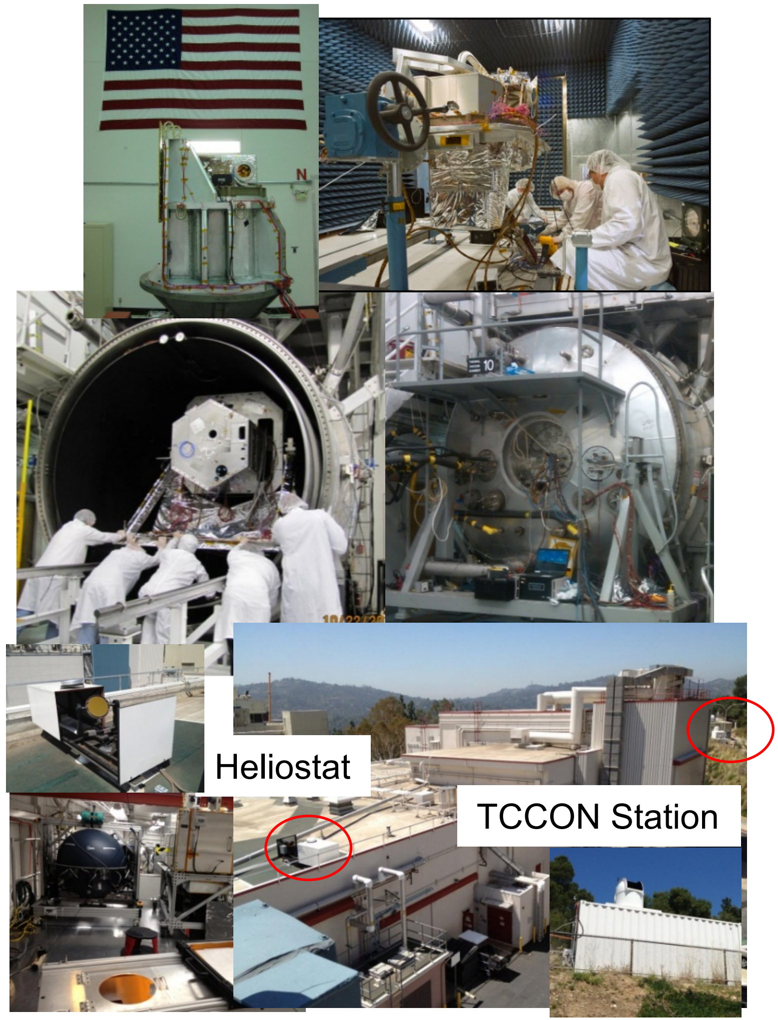
The GOSAT – OCO-2 Pre-Launch Cross-Calibration

- As part of their pre-launch testing programs, the GOSAT and OCO teams visited each other's test facilities and cross-calibrated their radiometric standards (Sakuma et al., 2010).
  - These measurements benefited both teams by identifying subtle errors and uncertainties in their pre-launch calibration hardware and testing procedures.
  - Many of the lessons learned from the OCO-GOSAT pre-launch calibration were adopted as parts of the OCO-2, OCO-3, and GOSAT-2 pre-launch calibration programs and have been incorporated into the GeoCarb calibration plan.
- The OCO-2 and OCO-3 teams took a further step by enlisting the direct participation of the National Institute of Standards and Technology (NIST) in the pre-launch radiometric calibration process (Rosenberg et al., 2017).
  - Similar methods and instruments can be adopted by other missions to radiometrically calibrate high-spectral-resolution NIR and SWIR spectrometers.

- Sakuma, F., et al.: OCO/GOSAT Preflight Cross-Calibration Experiment, IEEE Transactions on Geoscience and Remote Sensing, 48, 2010.
- Rosenberg, R. et al.: Preflight radiometric calibration of Orbiting Carbon Observatory 2. IEEE Trans. Geoscience Remote Sensing, 55, doi 10.1109/TGRS.2016.2634023, 2017.

Pre-Flight Instrument Characterization and Calibration

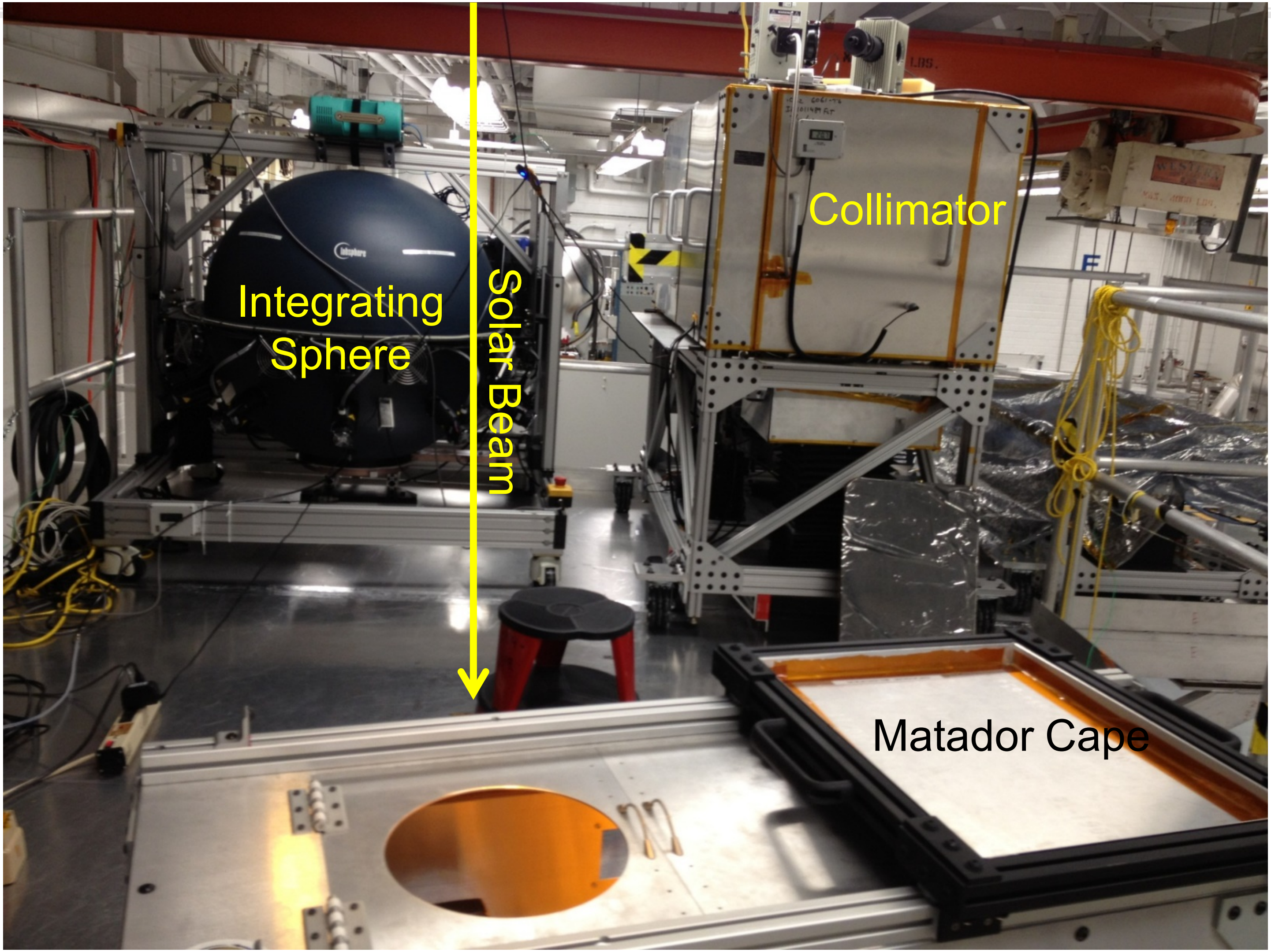
- Pre-flight testing quantifies key Instrument performance and knowledge parameters
  - **Geometric**
    - Field of view, Bore-sight alignment
  - **Radiometric**
    - Zero-level offset (bias)
    - Gain, Gain non-linearity
  - **Spectroscopic**
    - Spectral range, resolution, sampling
    - Instrument Line Shape (ILS)
  - **Polarization**
  - **Instrument stability**



Optical Ground Support Equipment

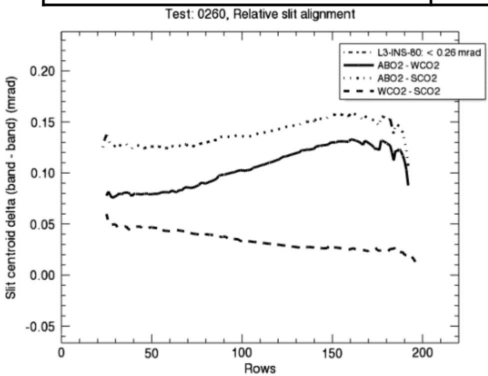
- **Collimator**: spatially-defined continuum and laser light sources to
  - Establish the spectrometer focus
  - Define instrument field of view (including slit alignment, spatial stray light)
  - Define the spectrometer instrument line shape and spectral scattered light
  - Determine the angle of polarization
- **Integrating Sphere**: spatially uniform continuum light sources to
  - Characterize and calibrate radiometric performance (minimum and maximum measureable signal, radiometric gain and its linearity, signal to noise ratio)
  - Provide a baseline for the pixel-to-pixel variability in gain
- **Step-scan FTS**: for assessing spectral stray light rejection
- **Heliostat**: acquire atmospheric spectra using direct sunlight
  - Validate the instrument line shape and dispersion
  - Test gain linearity and transient response over a range of illumination
  - Provide an end-to-end test of instrument calibration & retrieval algorithm performance, through comparisons with TCCON XCO2 retrievals

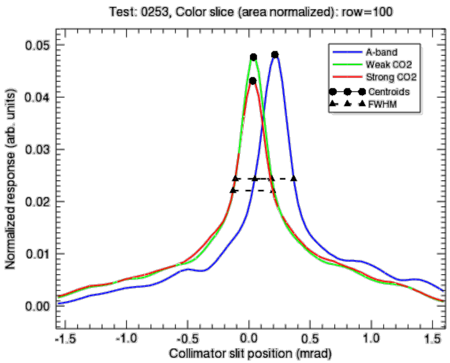
Calibration Deck

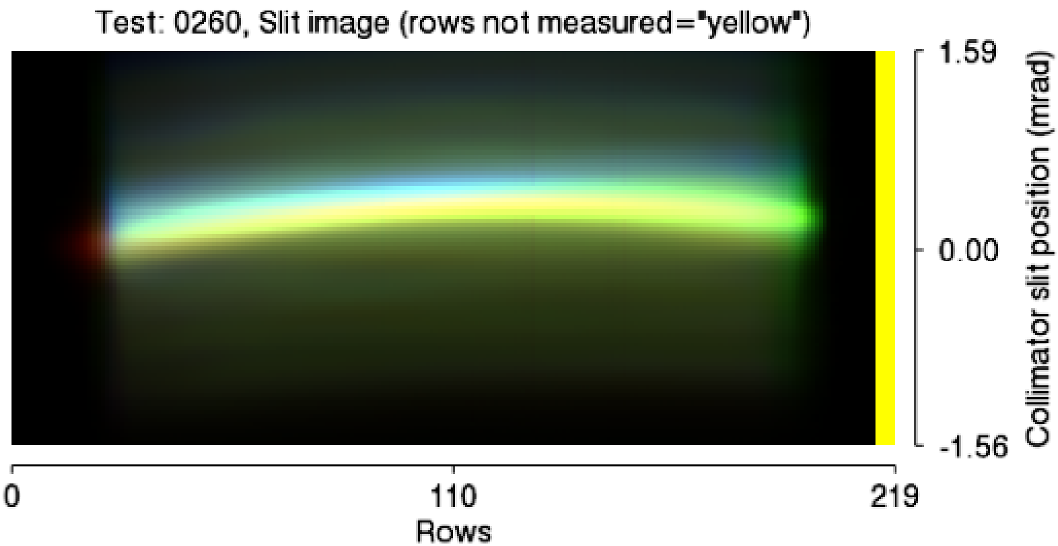


Geometric: Slit Alignment

Requirement	Value	Measured	Notes
Slit Width	< 2 mrad	~**0.5** mrad (typical) **0.7** mrad (worst case)	~3x Margin
Slit Misalignment	< 0.26 mrad	~**0.1** mrad (typical) **0.15** mrad (worst case)	~70% Margin

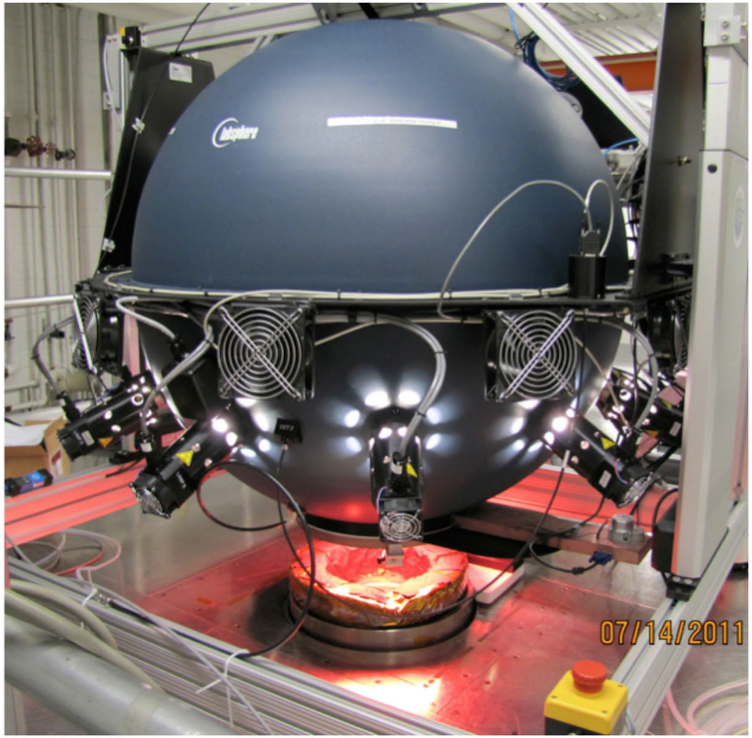


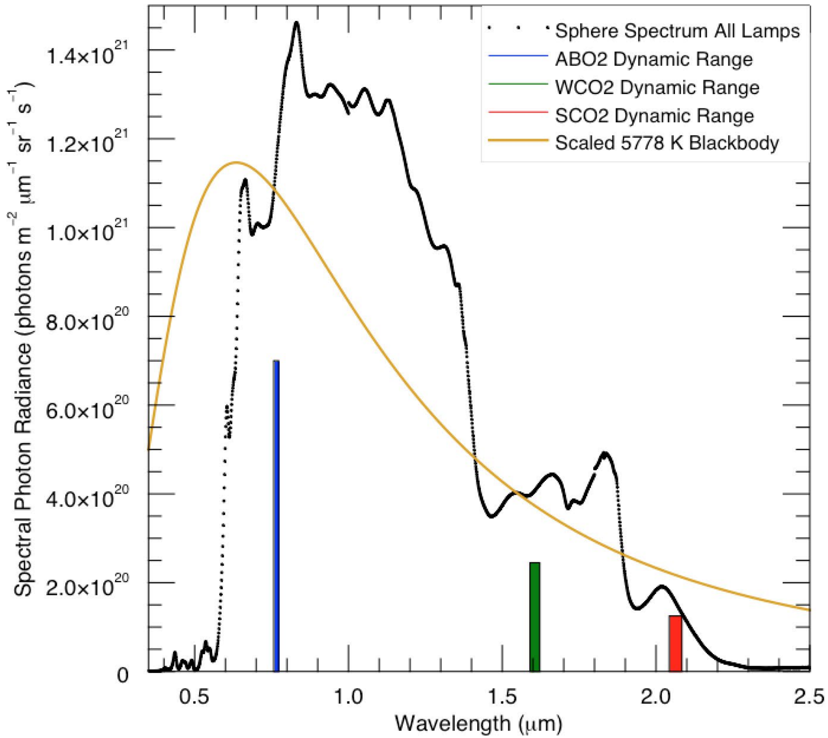




Impacts of slit misalignment and scene non-uniformity mitigated by defocusing the entrance telescope.

Radiometric Calibration with the Integrating Sphere

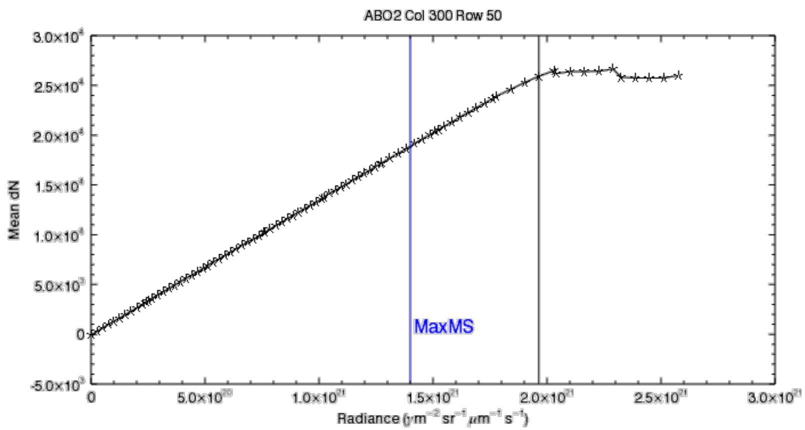


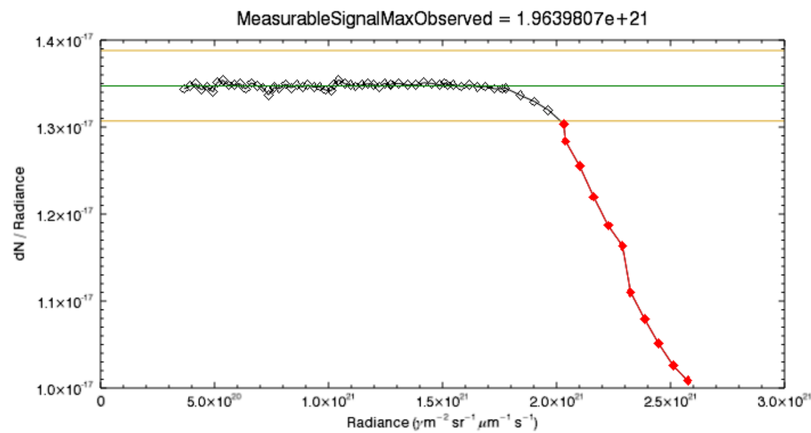


An integrating sphere with 10 lamps (one of which had a variable aperture) was the primary tool used for calibrating the radiometric performance of the instrument. The performance of the sphere (installed above the TV chamber in the TV test configuration) was calibrated in collaboration with NIST.

Radiometric: Dynamic Range

Requirement	Value	Measured	Notes
Max Measureable Signal – A-band	≥ 1.4 x 10^{21} *	**~1.8 x 10^{21} ***	• ~30% Margin
Max Measureable Signal – Weak CO_2	≥ 4.9 x 10^{20} *	**> 8.7 x 10^{21} ***	• Very large margins • Sphere isn't bright enough to saturate the detectors in CO_2 channels
Max Measureable Signal – Strong CO_2	≥ 2.5 x 10^{20} *	**> 3.8 x 10^{21} ***	

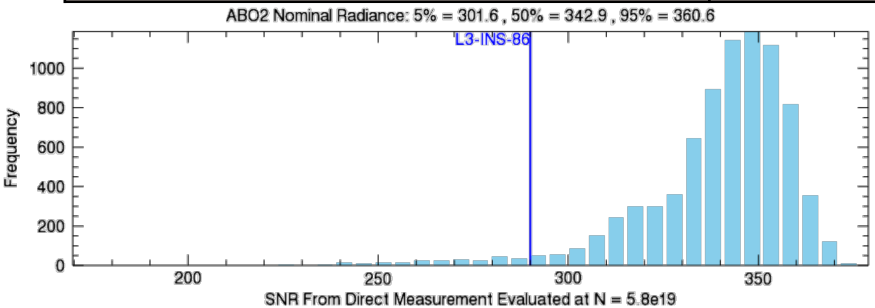


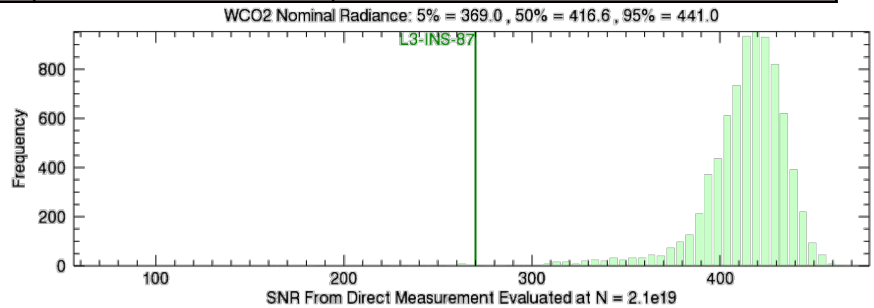


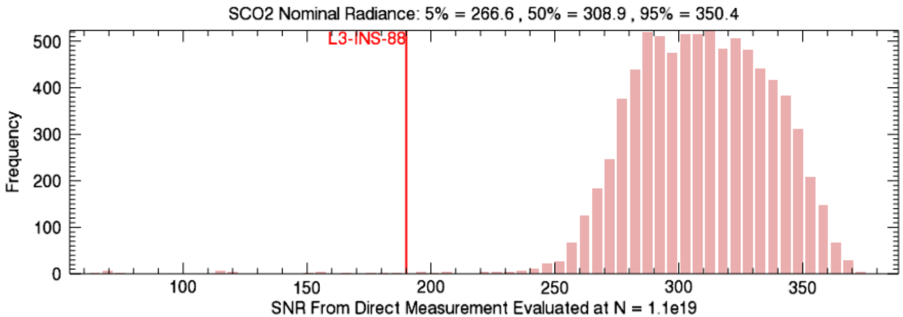
* OCO Radiance Units are: photons/m^2/sr/µm/s

Radiometric: Signal-to-Noise Ratio at Nominal Signal

Requirement	Value	Measured	Notes
Signal-to-Noise Ratio – A-band	> 290	**302 – 361**	At 5.9 x 10^{19} photons/m^2/sr/μm/s
Signal-to-Noise Ratio – Weak CO_2	> 270	**369 - 441**	At 2.1 x 10^{19} photons/m^2/sr/μm/s
Signal-to-Noise Ratio – Strong CO_2	$\geq$ 190	**267 - 350**	At 1.1 x 10^{19} photons/m^2/sr/μm/s

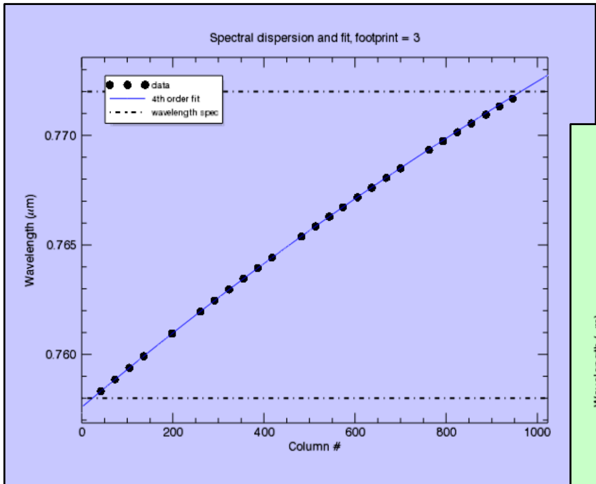


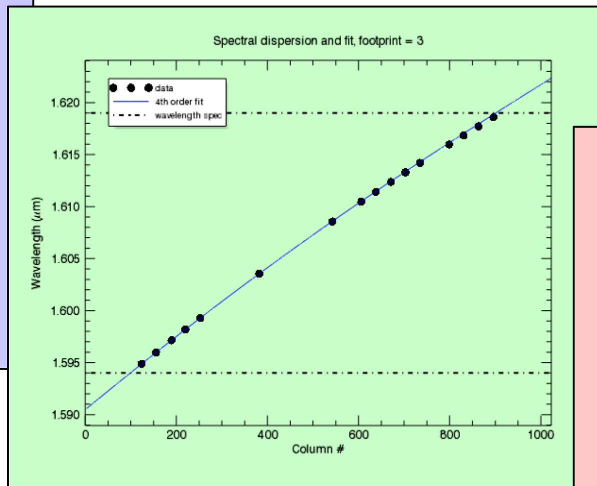


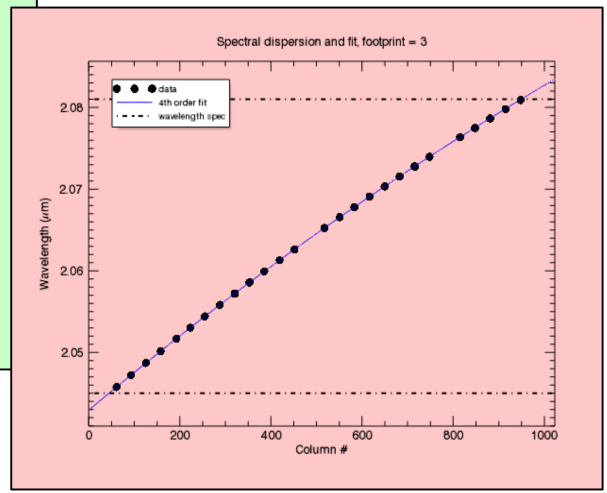


Spectroscopic: Spectral Range

Requirement	Value	Measured	Notes
Spectral Range – A-band	758 to 772 nm	**757.6 – 772.6** nm	Bands are well centered for OCO-2
Spectral Range – Weak CO_2	1,594 – 1,619 nm	**1,590.6 – 1,621.8** nm	
Spectral Range – Strong CO_2	2,045 – 2,082 nm	**2,043.1 – 2083.3** nm	

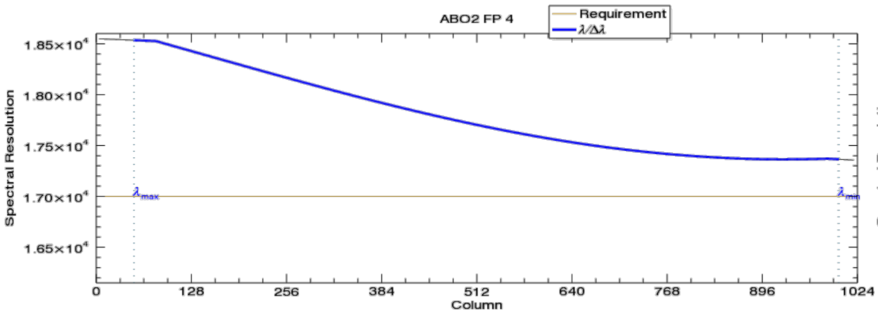


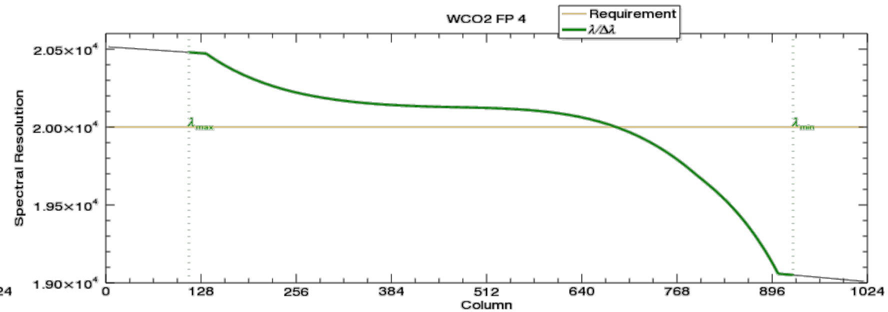


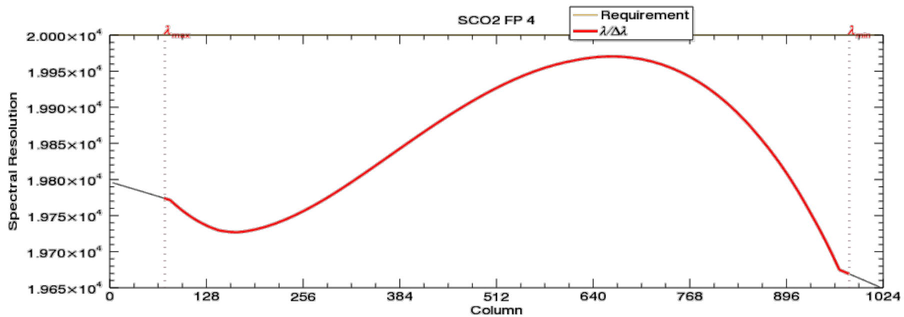


Spectroscopic: Spectral Resolution

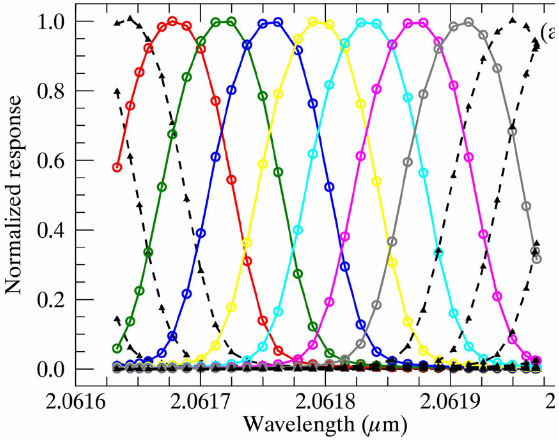
Requirement	Value	Measured	Notes
Spectral Resolution – A-band	> 17,000	17,500 – 18,500	Resolving power is slightly low in CO2 channels. L2 Algorithm Team found found no impact on OCO-2 Level 1 requirements
Spectral Resolution – Weak CO_2	> 20,000	19,100 – 20,500	
Spectral Resolution – Strong CO_2	> 20,000	19,700 – 19,900	

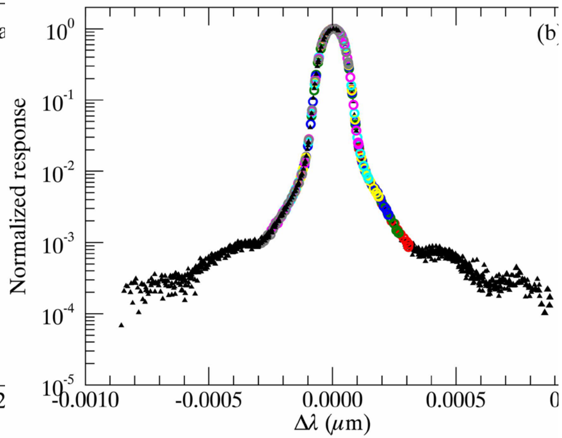


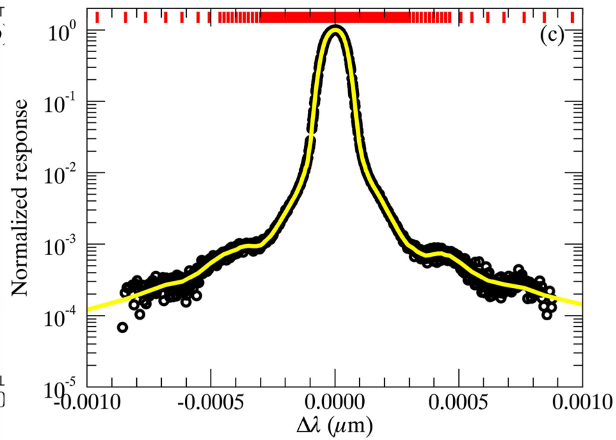




Characterizing the Instrument Line Shape (ILS) with Tunable Diode Lasers







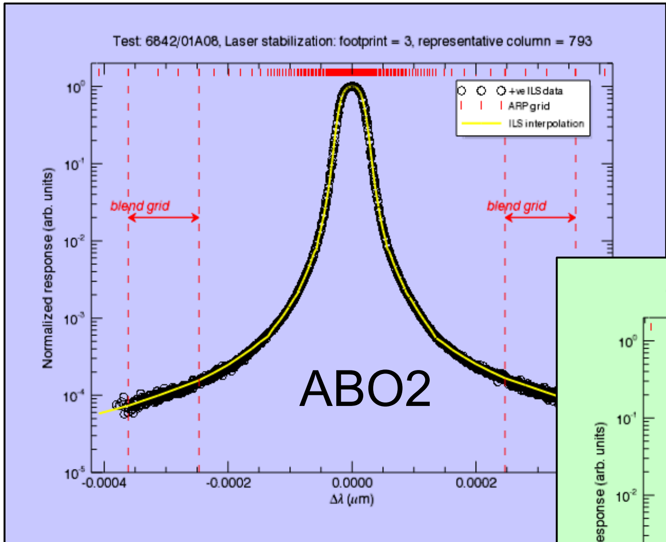
Record Laser Diode Scans over 5-10 adjacent spectral samples at 40 to 50 wavelengths ranges throughout each channel.

Combine measurements from all scans of each spectral sample within each scan range to create a over-sampled combined dataset

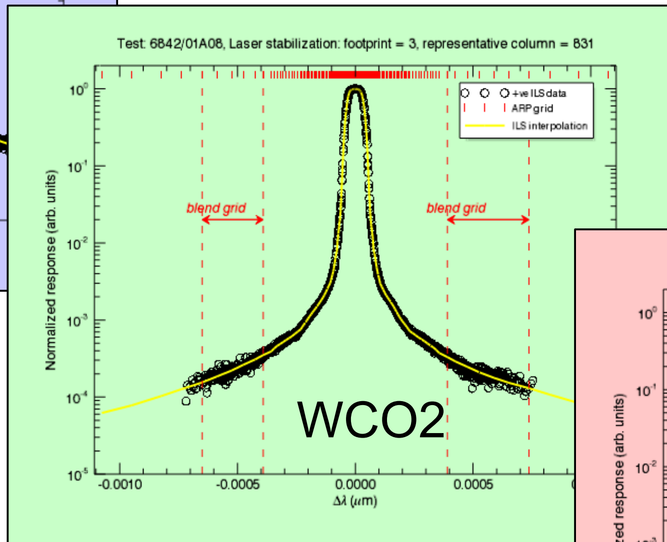
Produce a smooth fit to the combined data set for each sample.

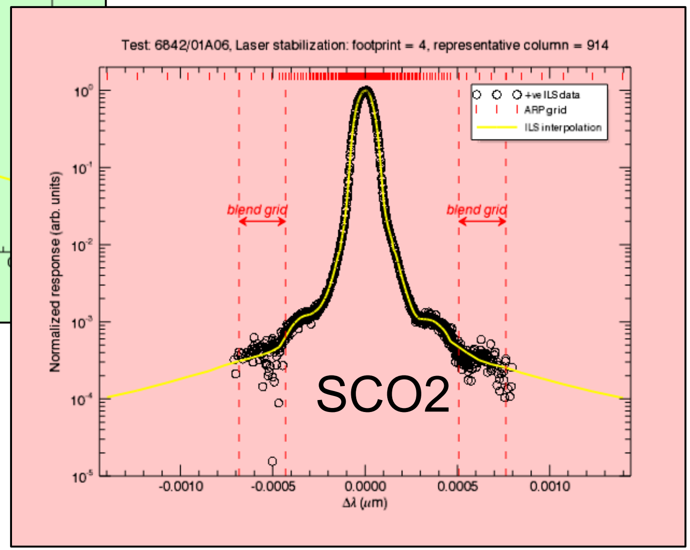
Finally, the ILS was assumed to vary smoothly over each channel such that the mean ILS recorded for each 5-10 sample range can be attributed to the center wavelength of that range, and the ILS of intermediate samples can be linearly interpolated between these ranges. The ILS of each spectral sample is then described on a un-equally-spaced 200-point grid (see red dashes in figure above).

Spectroscopic; Instrument Line Shapes



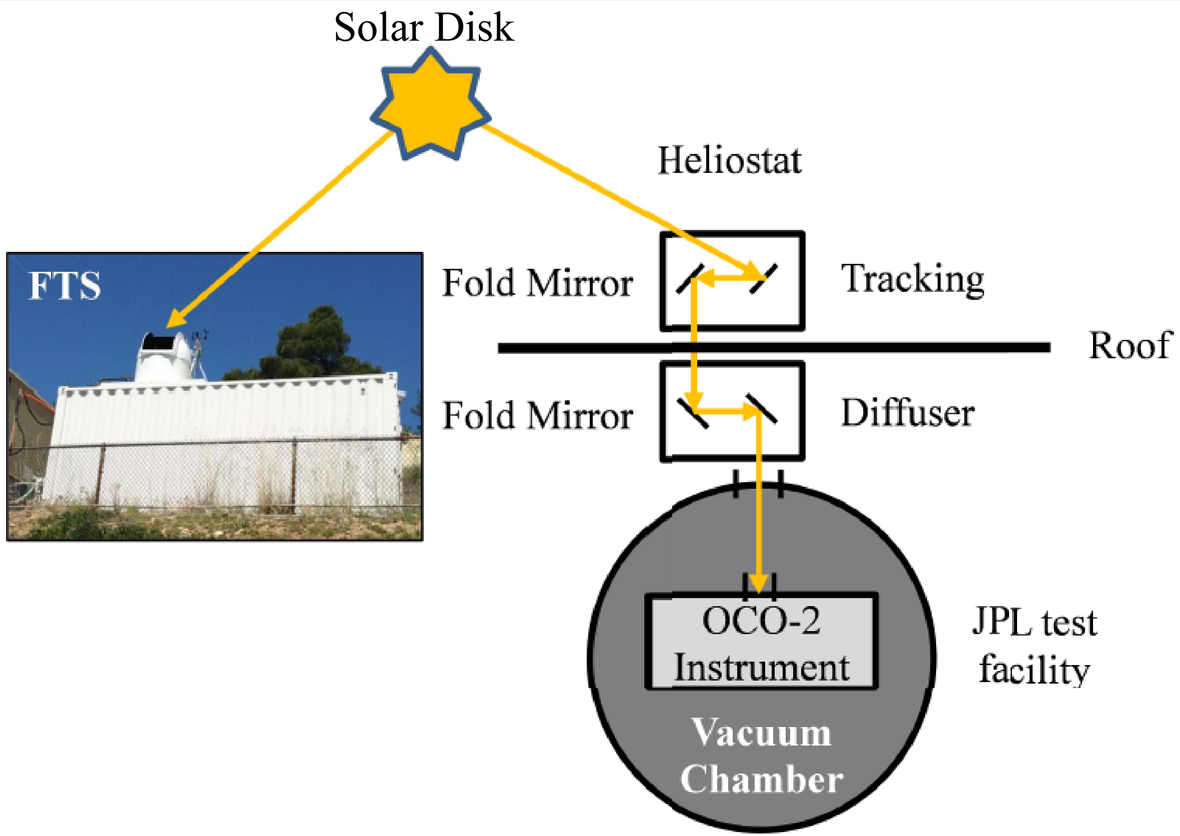
- Examples of tunable diode lasers scans across each of the three spectral ranges.
- This method could characterize the ILS shape over a dynamic range of 1000 to 10000.





These results provided information about the ILS shape, width (resolving power) and dispersion, but these results were not adequate to meet the OCO-2 requirements

Verifying the ILS with Direct Solar Measurements

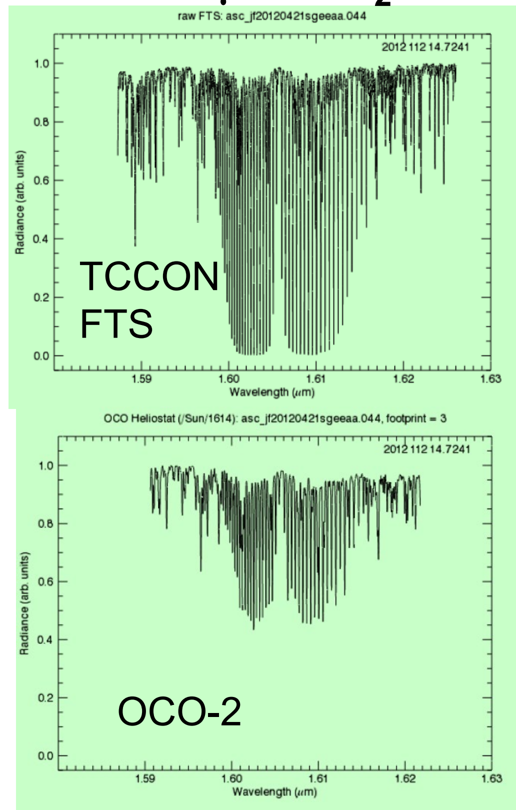


A heliostat on the roof of the building housing the thermos vacuum chamber allowed the acquisition of spectra of direct sunlight. Simultaneous observations from a nearby TCCON station served as a high resolution reference standard.

Pre-flight Heliostat/TCCON Observations Verify End-to-End Instrument Performance

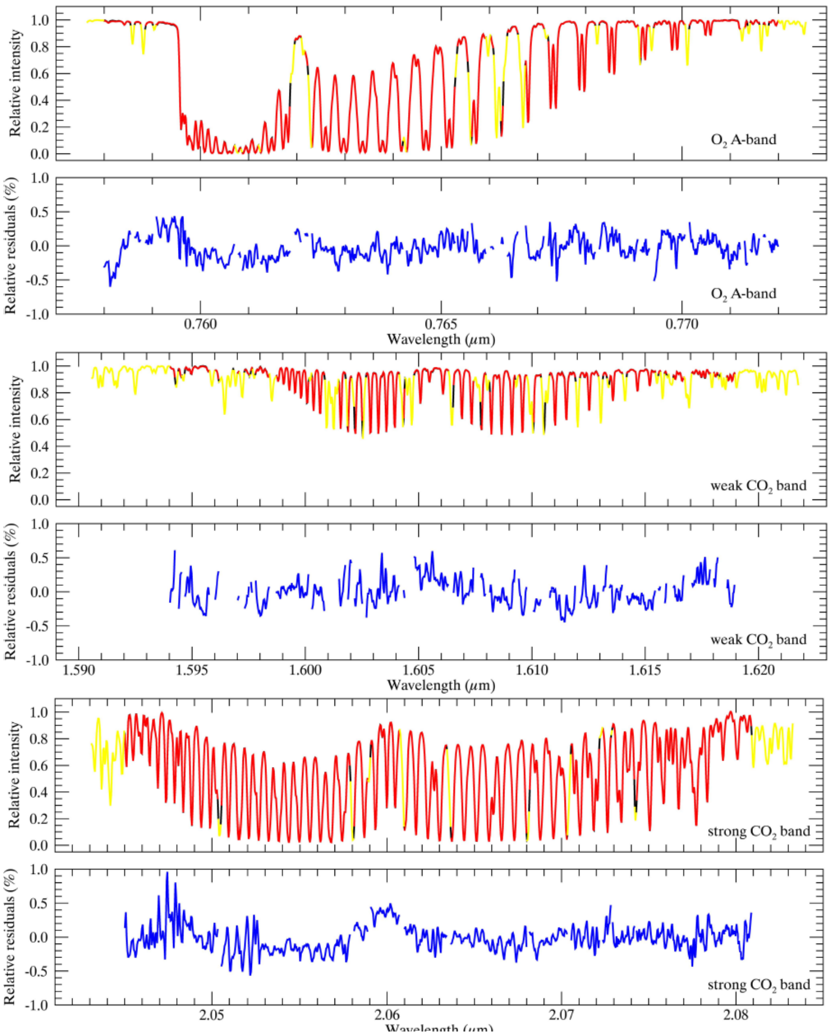
Observations of the sun with the flight instrument taken during TVAC tests provide an end-to-end verification of the instrument performance.

1.6 μm CO_2



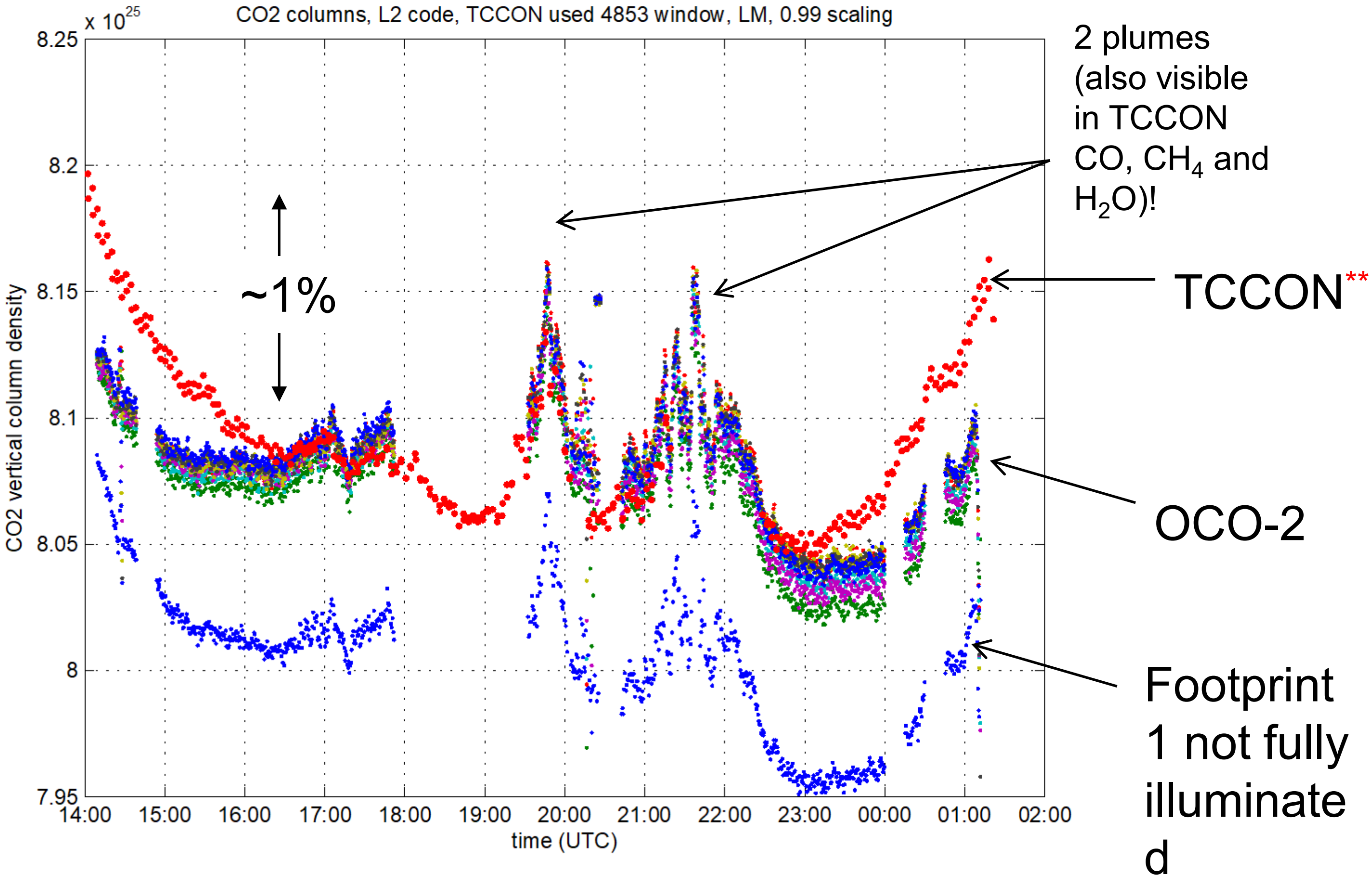
21 April 2012

Example of OCO-2/TCCON Fits



- TCCON spectra (R ~ 200,000) were convolved with the OCO-2 ILS fits derived from the laser diode measurements and compared to the spectra recorded by the OCO-2 instrument
- Strong solar lines had to be eliminated from these fits because the TCCON and OCO-2 sample the solar disk in differently
  - TCCON observes only the middle ~10% of the solar disk
  - OCO-2 samples the complete disk, including the solar limbs, and thus sees lines with more Doppler broadening.
- Typical residuals were < 0.5% after an optimization step (ILS width and dispersion adjusted)

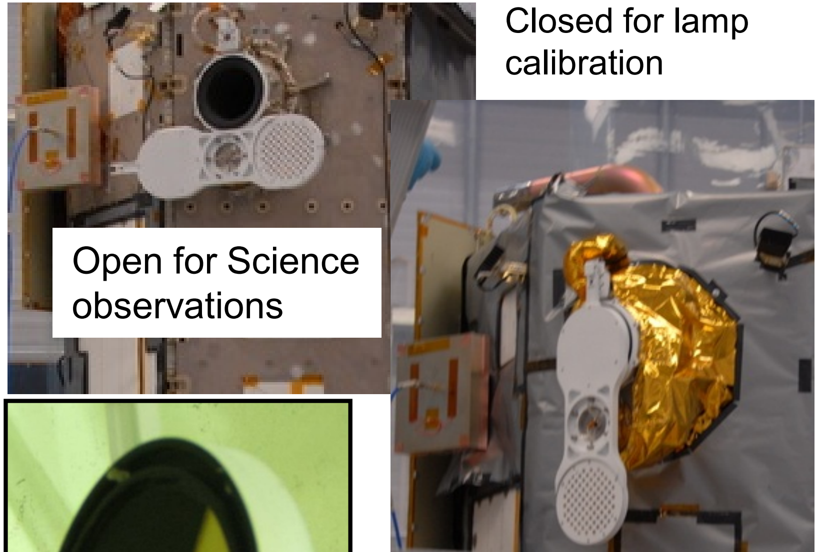
CO_2 Column Retrievals from the Strong CO_2 (SCO2) Channel at 2.06 µm



7 of the 8 footprints in the SCO2 channel produce CO_2 column estimates within ±0.25%.

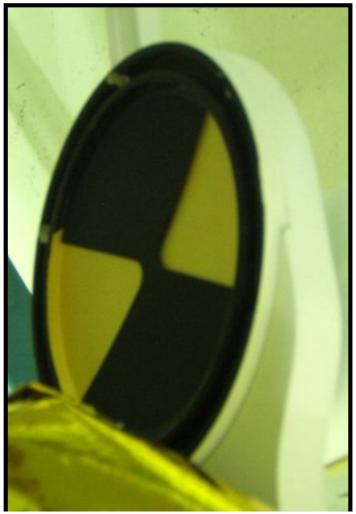
** *TCCON does not use this channel to retrieve X_{CO2}. This is a custom retrieval by D. Wunch.*

Verifying Radiometric Calibration: The On-board Calibration System



Open for Science observations

Closed for lamp calibration

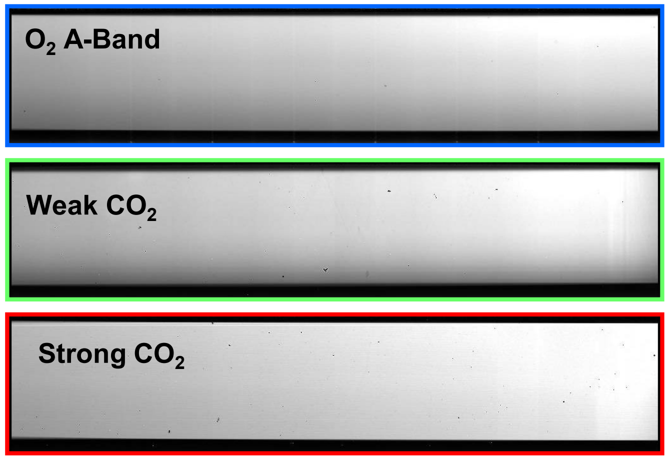


Reflective diffuser

Telescope baffle assembly, showing lamps for flat fields

The on-board calibration (OBC) system consists of a rotating calibration paddle that carries:

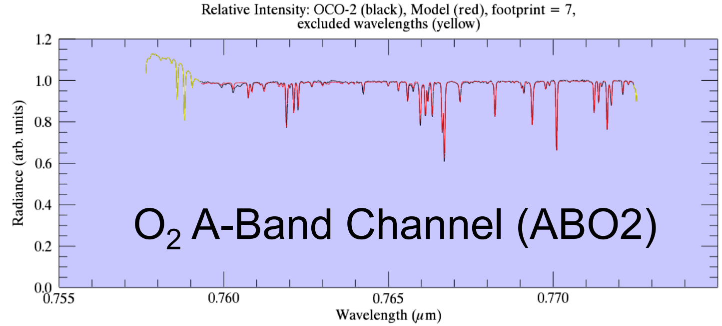
- an aperture cover, with a reflective diffuser illuminated by on-board lamps for monitoring pixel-to-pixel variations
- A transmission diffuser for making observations of the solar disk for monitoring radiometric calibration

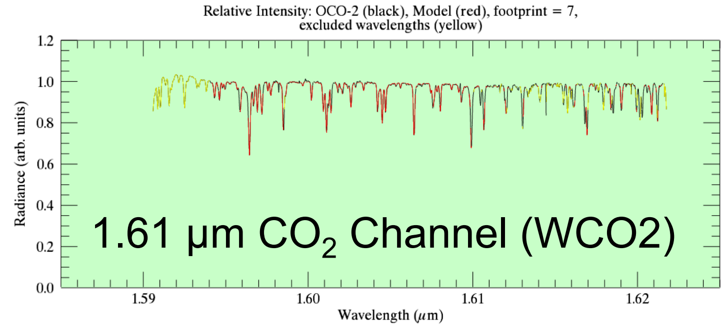


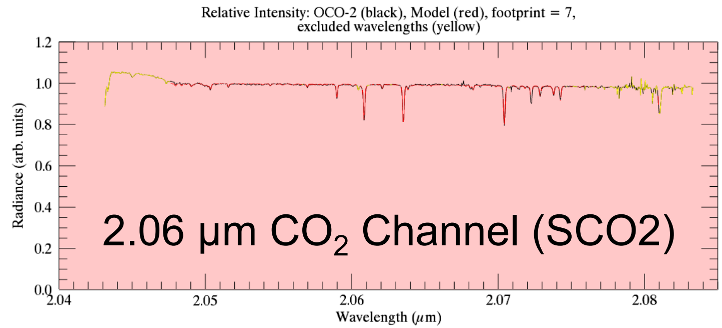
Lamp “flat fields” from each channel.

Solar Radiometric Calibration

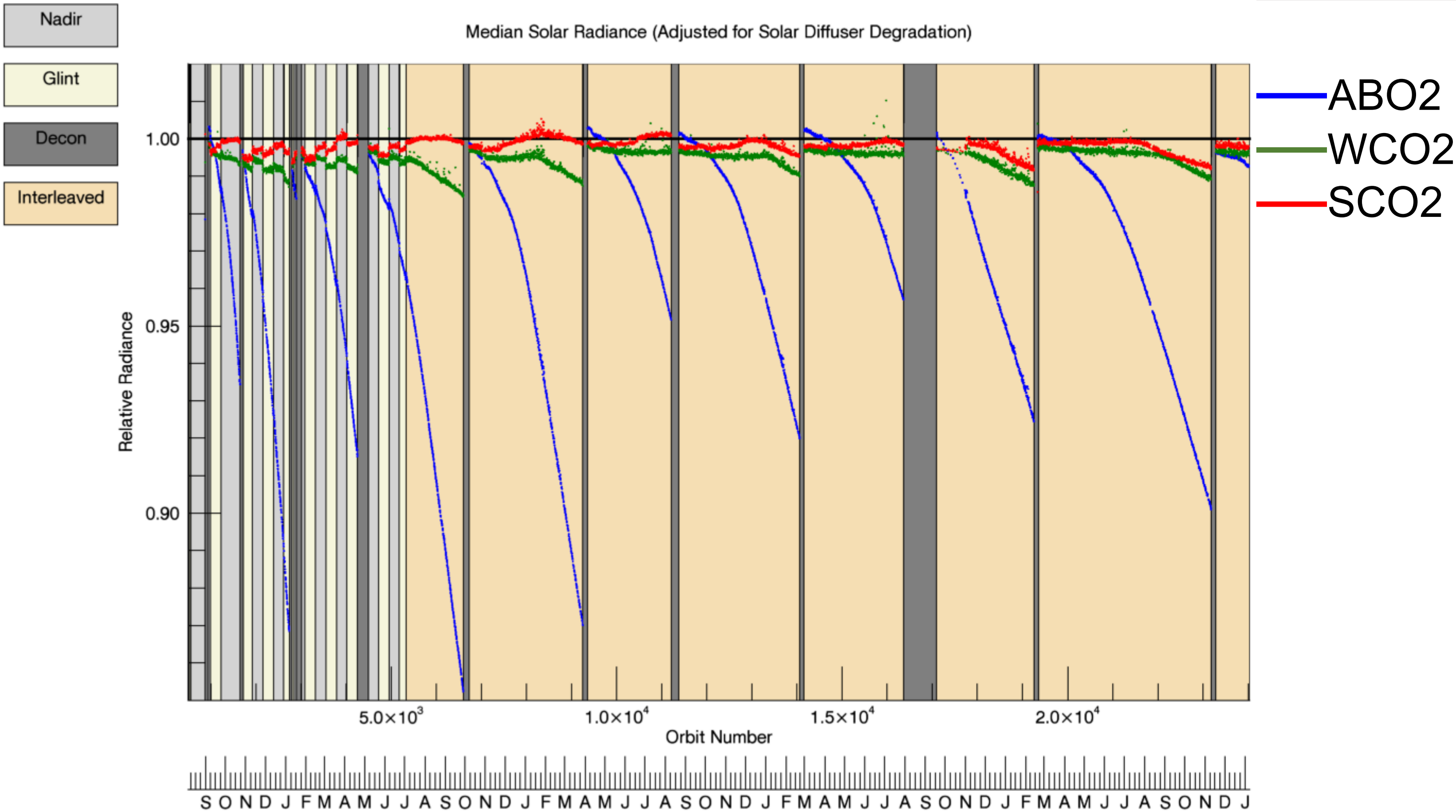
- Observations of the Sun are acquired through a diffuser on ~12 orbits each day
- These spectra are used to track changes in the radiometric calibration
- Solar lines are also monitored to track changes in the instrument line shape (ILS)
    - Observations of the Sun are acquired over full dayside orbits, providing thousands of observations with Doppler shifts varying from +/- 7 km/sec
    - These data are corrected for Doppler shift and combined for produce massively oversampled solar line data
    - No changes in the ILS have been seen







Throughput Trending – Solar Calibration



Routine solar observations are used to track ice accumulation on FPA's, which can produce rapid changes in the sensitivity of the O2 A-band channel.

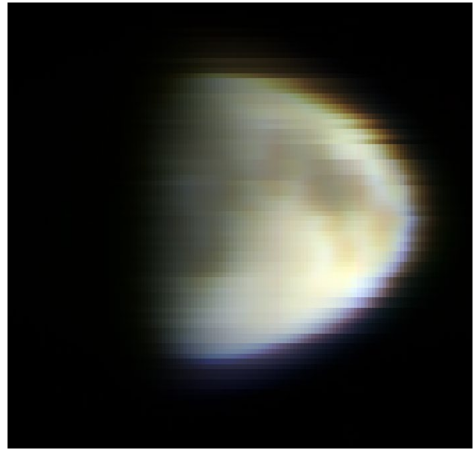
A-Band Channel Sensitivity Variations

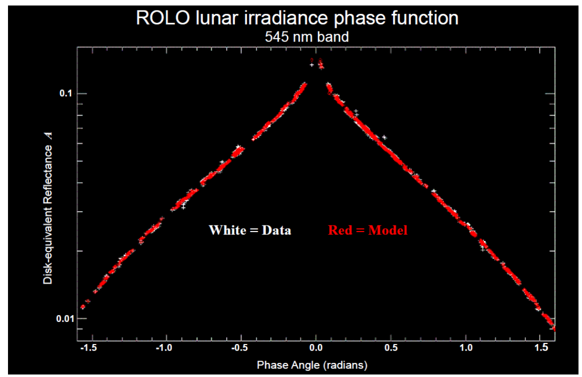
- The sensitivity of the OCO-2 ABO2 channel has varied over time, while the WCO2 and SCO2 show much less variability
- The ABO2 sensitivity degradation has two components
  - A "fast degradation" reversed by decontamination activities
    - This component has been attributed to temporary degradation of the anti-reflection coating on the A-band focal plane array detector (FPA) due to the accumulation of a thin (< 100 nm) layer of ice on the FPA
  - A monotonic "slow degradation"
    - Lunar and Vicarious Calibration measurements indicate that this change is due to degradation of the solar diffuser rather than a throughput loss in the instrument

These changes have become a major focus of the OCO-2 on-orbit radiometric calibration program

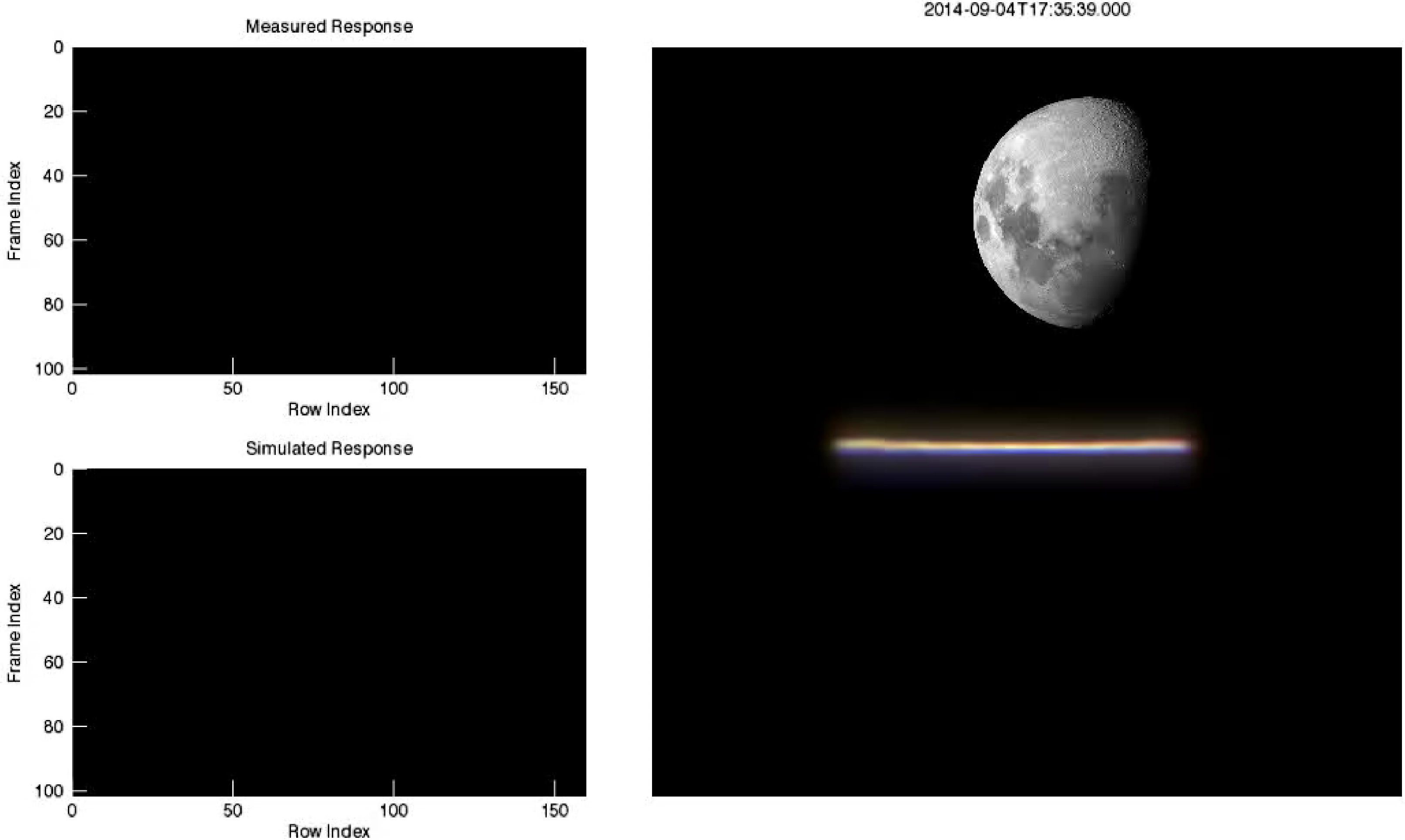
Lunar Calibration

- Observations of the Moon are acquired twice each month to support three calibration activities
  - Geometric calibration: Relative pointing of the instrument boresight and the star tracker
  - Co-alignment of 3 spectrometer slits
  - Relative radiometric calibration: Trending the throughput of the science data path (with no diffusers or attenuators) and trending the performance of the solar calibration diffuser
- The Moon is typically observed in ¾ gibbous phase and near full
  - Gibbous phase is better for geometric calibration, because the star tracker is partially occulted by the Earth near full moon
  - Both gibbous and full phases yield useful calibration data, but gibbous phase is more highly polarized





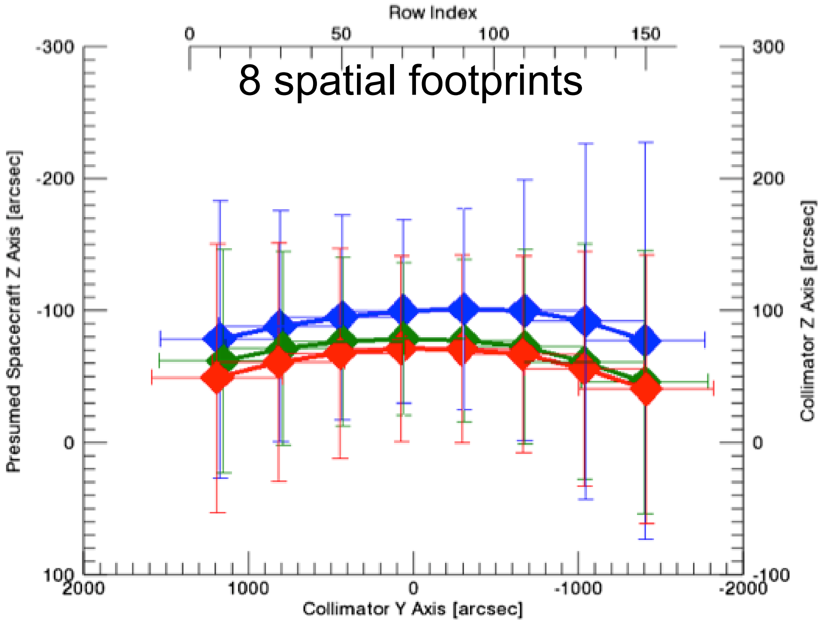
Geometric Calibration using the Moon



Typical scan of the spectrometer slit across the lunar disk.

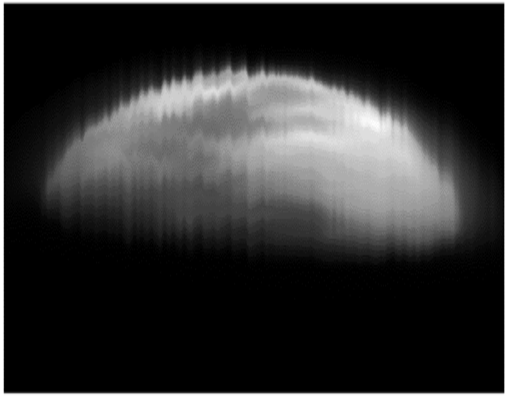
Boresight Alignment of the Spectrometers

- The OCO-2 and OCO-3 instruments incorporate 3 spectrometer
- The three slits were aligned prior to launch, but there was some concern that the slits might move during launch
- Observations of the moon are used to monitor the alignment of the spectral slits of the 3 spectrometers

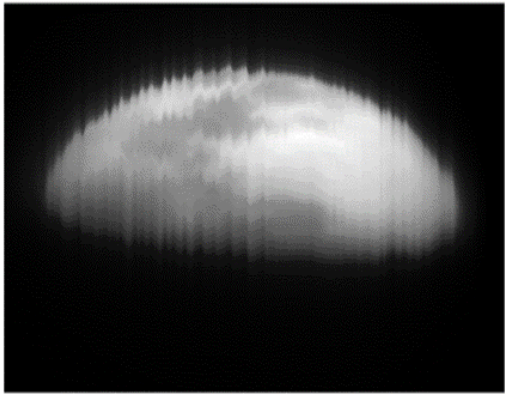


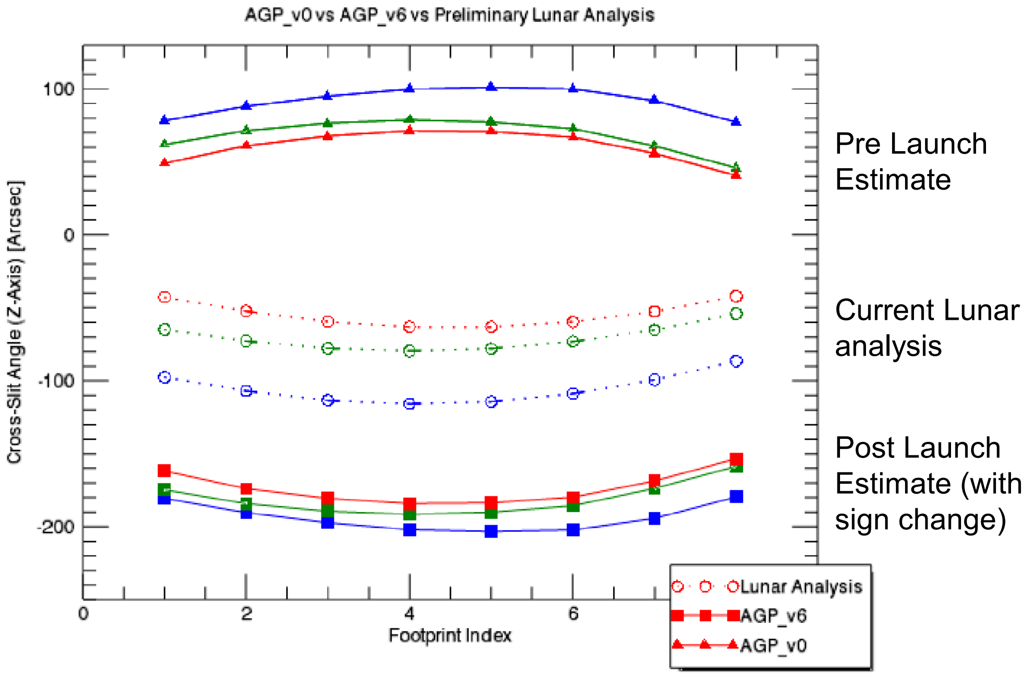
Lunar Geometric Analysis

Observed



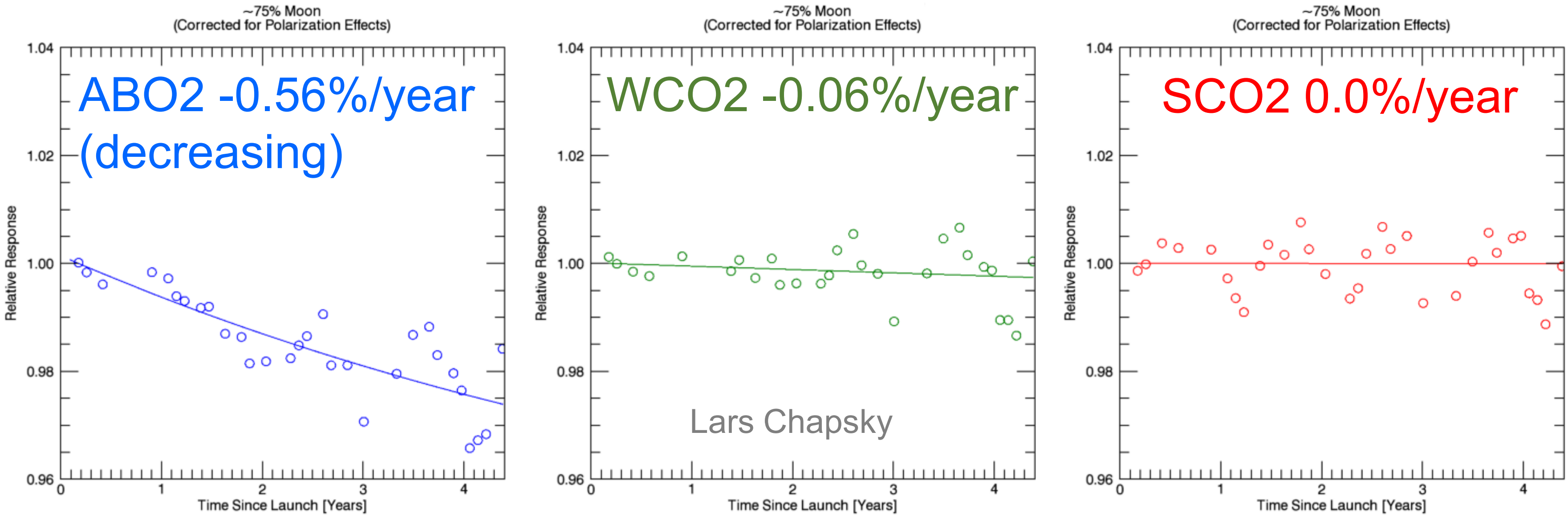
Simulated





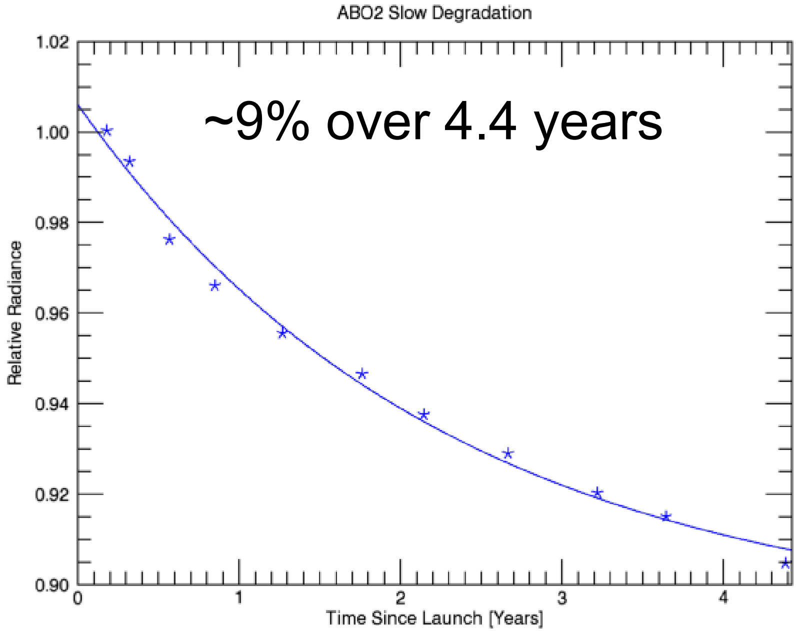
- Scans across the crescent moon are collected each month for geometric and radiometric calibration
- These data re being used to determine the pointing offsets.

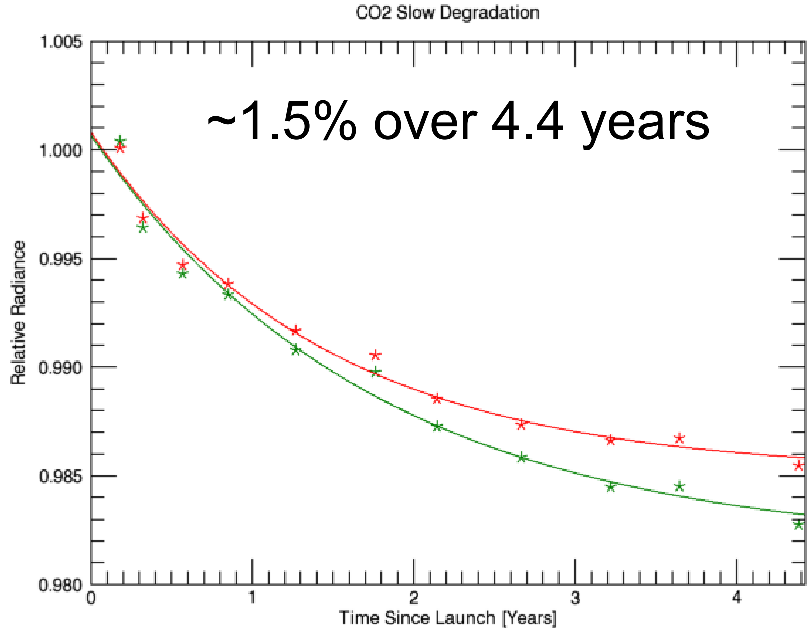
Lunar Calibration Tracks Science Throughput



Observations of the Moon acquired twice each month (at 75% phase and full) track the long term degradation of the throughput of those parts of the optical system used for science observations. The largest changes (~2.5% over 4.4 years) are seen in the ABO2 channel, but the rate of change is decreasing over time.

Degradation of the Solar Diffuser Tracked Using Comparisons of Lunar and Solar Observations

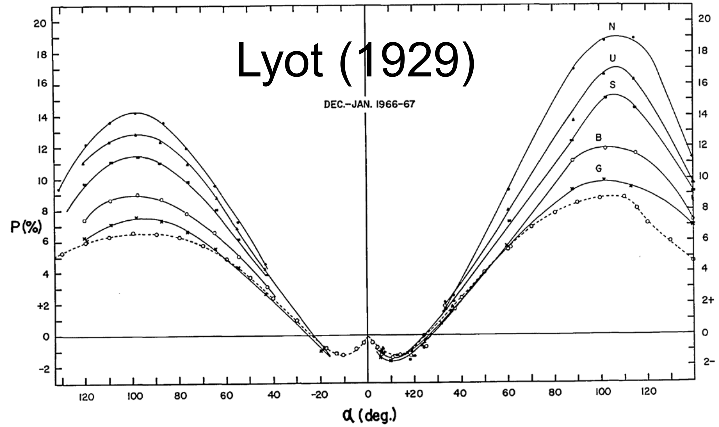




Comparisons of Solar (with diffuser) and Lunar (without diffuser) observation are used to track the long term degradation of the solar calibration diffuser. The largest changes are seen in the O_2 A-Band channel, but the rate of change in decreasing in all three channels.

Can the Moon be used as a Polarimetric Standard

- The polarimetric properties of the moon were studied intensely in the early 20th century
  - Primary goal was to study the composition of the lunar regolith
  - Showed that polarization was spatially variable but stable
- Most of these observations used visible wavelengths
  - Moon is more strongly polarized at short wavelengths
  - Sensors available at the time were limited to wavelengths < 1.1 microns
- New NIR and SWIR polarimetric observations of the moon are needed for GHG missions



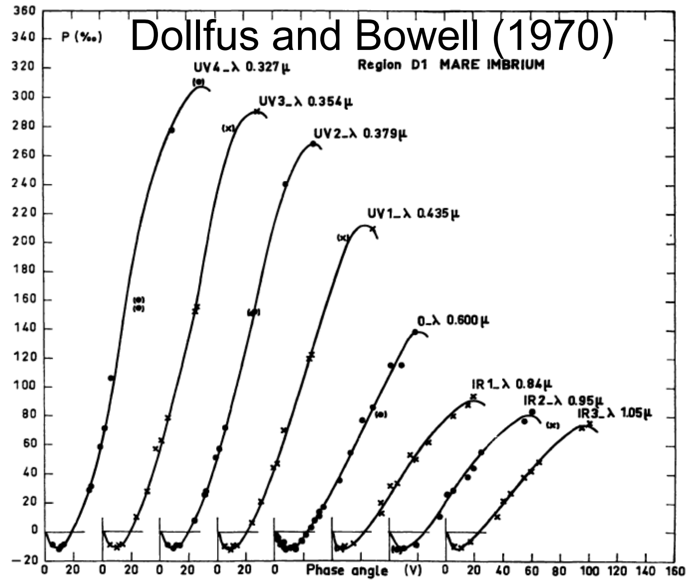
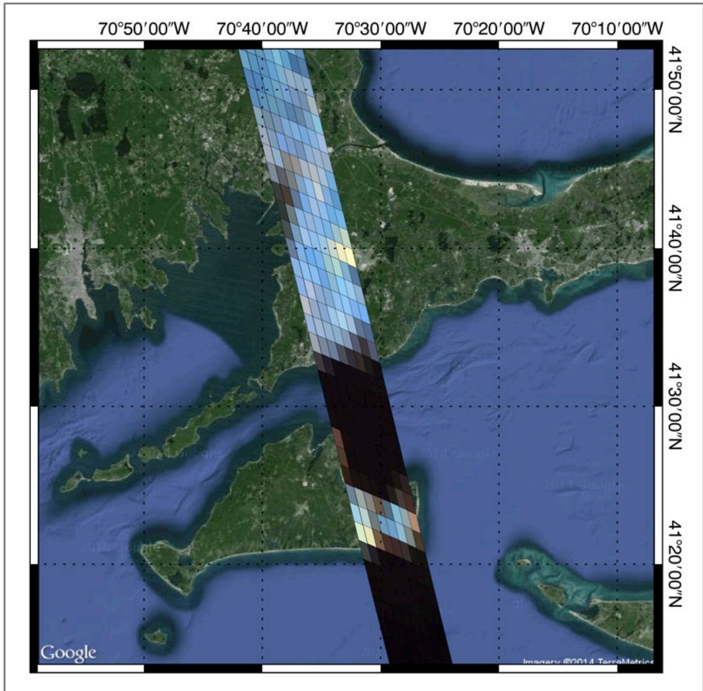
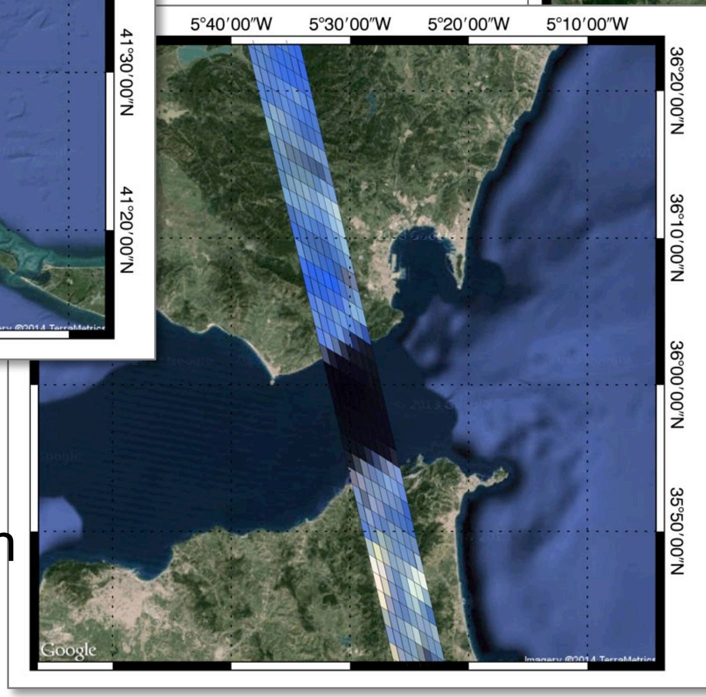
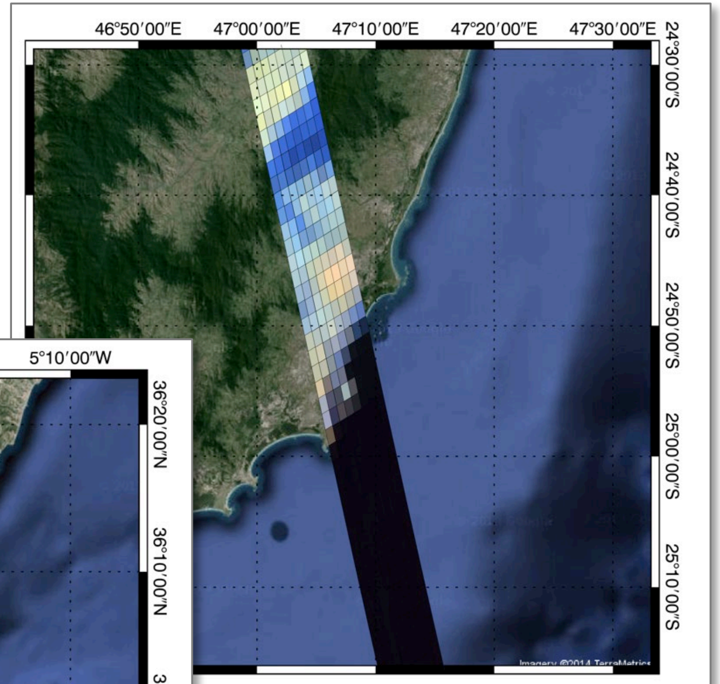


Fig. 2 to 15. Curves of polarisation in 8 wavelengths for 14 selected areas of the lunar surface (diameter 65″)

Geolocation Performance Verified with Surface Targets – Coastline Crossings



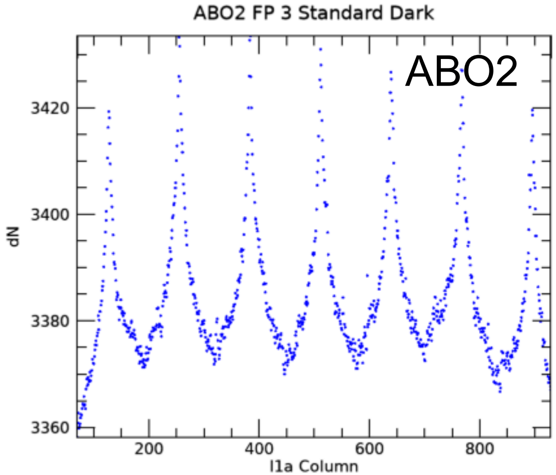


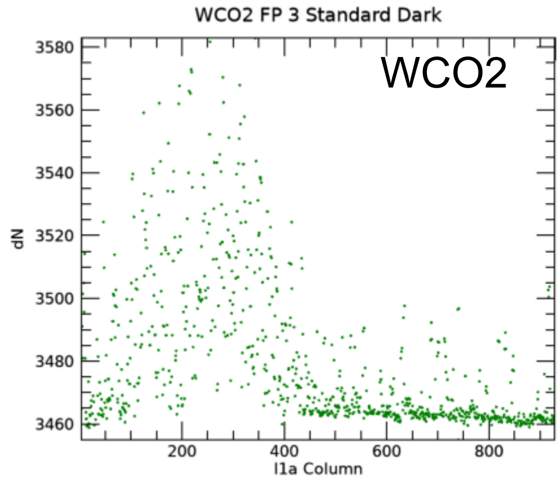


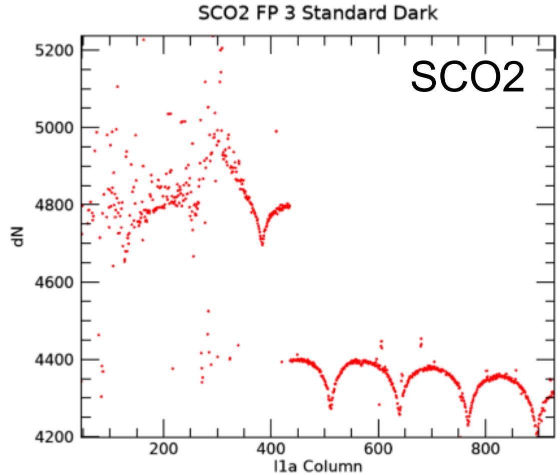
Pointing errors < 1/6 of a footprint can produce large (>1 ppm) biases in regions with rough topography.

Overflights of coastlines are used to validate pointing and geolocation

Dark Trending





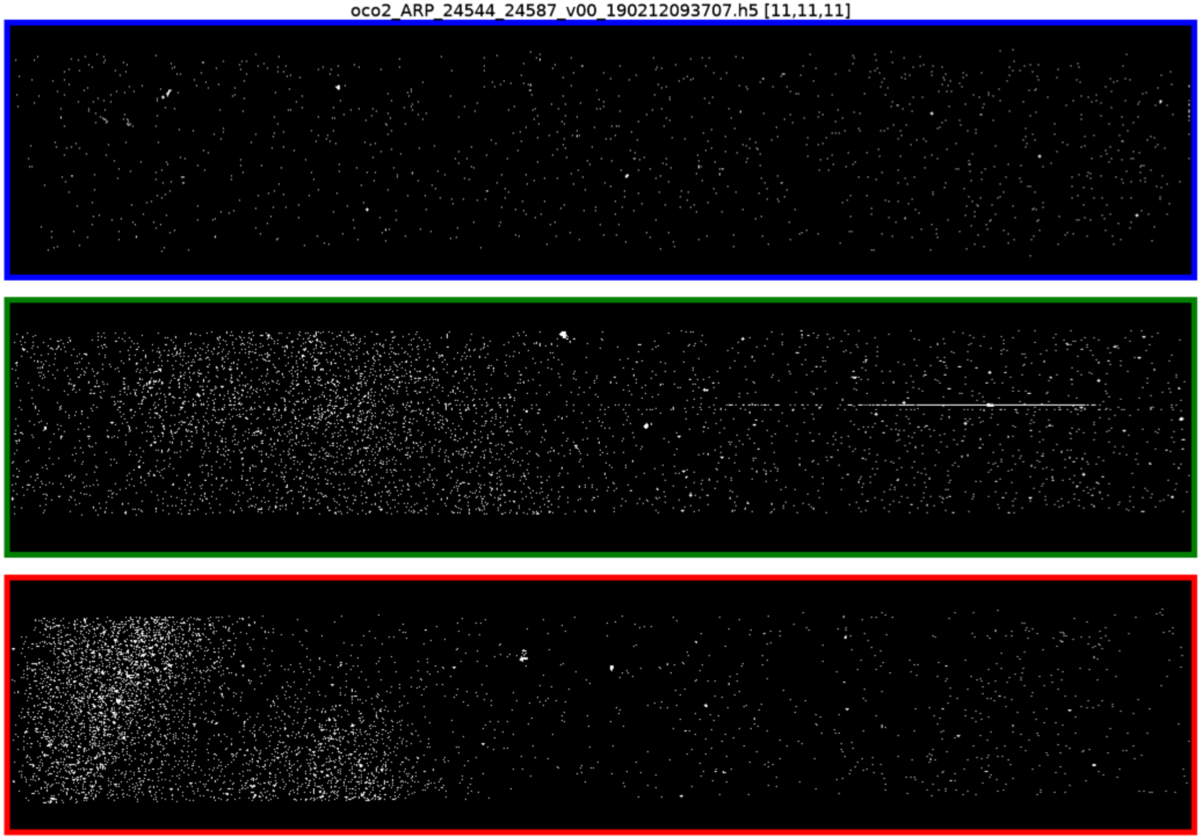


Dark Cal measurements are collected at twice on 12 orbits each day to track variations in the dark response. Half are performed in single-pixel mode and half are in sample mode.

The spatial distribution of the ABO2 dark response is determined primarily by amplifier readout. The spatial response of the WCO2 dark response is dominated by anomalous (but not bad) pixels. The dark response in the SCO2 channel reflects both amplifier gain differences and thermal emission.

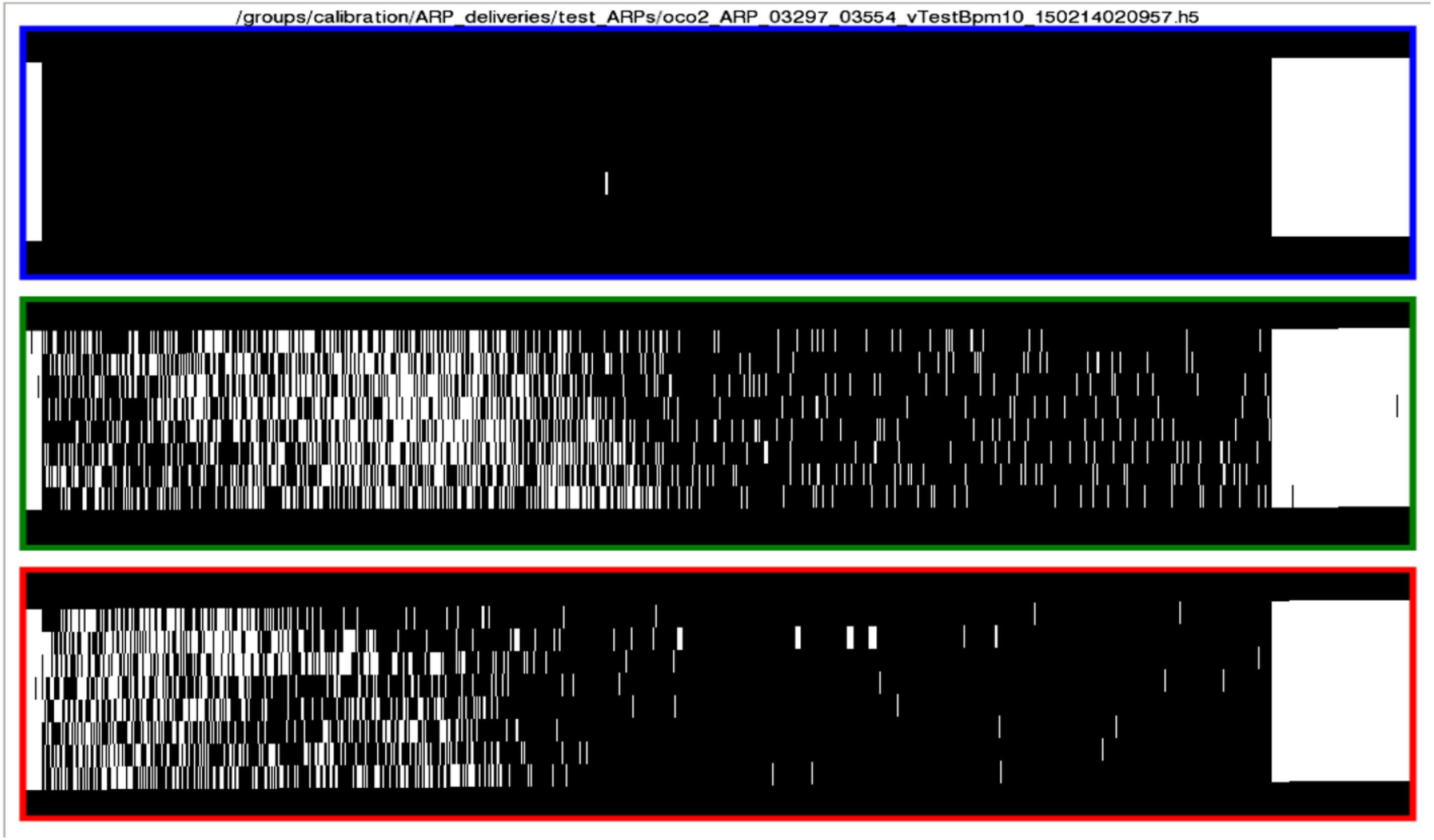
In the ABO2 channel, the dark response is most sensitive to the FPA temperatures. For the SCO2 channel, the dark response depends on both the FPA temperature and the optical bench temperature.

Bad Pixel Maps



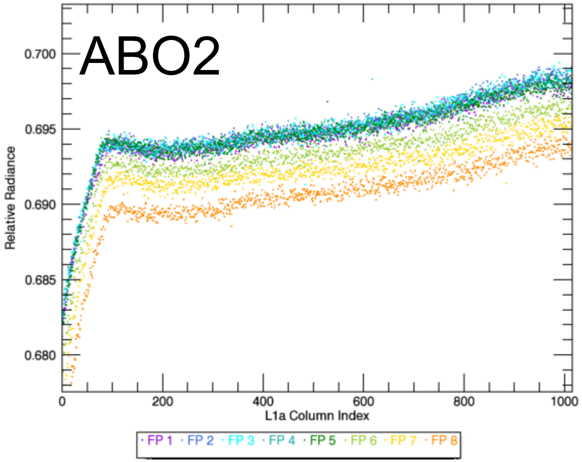
Bad pixel maps are updated by analyzing "single-pixel" dark and lamp flats. The bad pixel maps changed substantially between the TV tests and launch, but more slowly since the instrument has been in orbit.

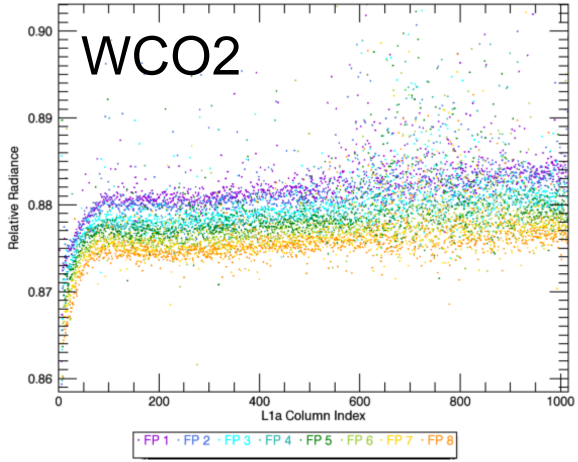
Bad Sample Lists

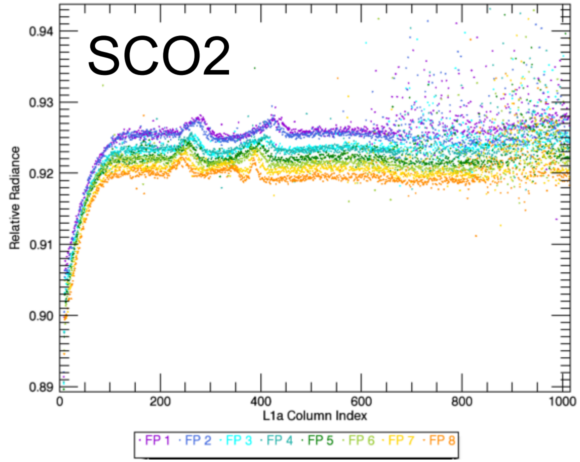


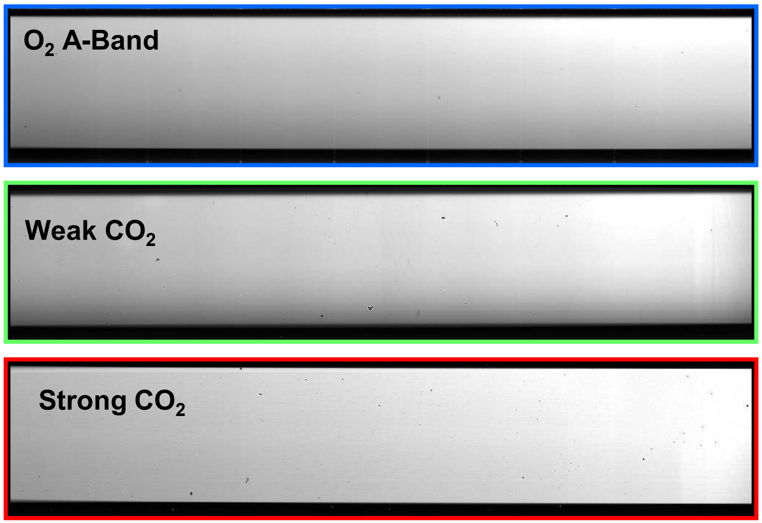
Each spectral sample consists of ~20 along-slit pixels that are summed on board. Bad sample lists are updated as needed to omit 20-pixel spectral samples that are not adequately corrected in Bad Pixel Maps.

Using Lamp Radiances to Trend Gain



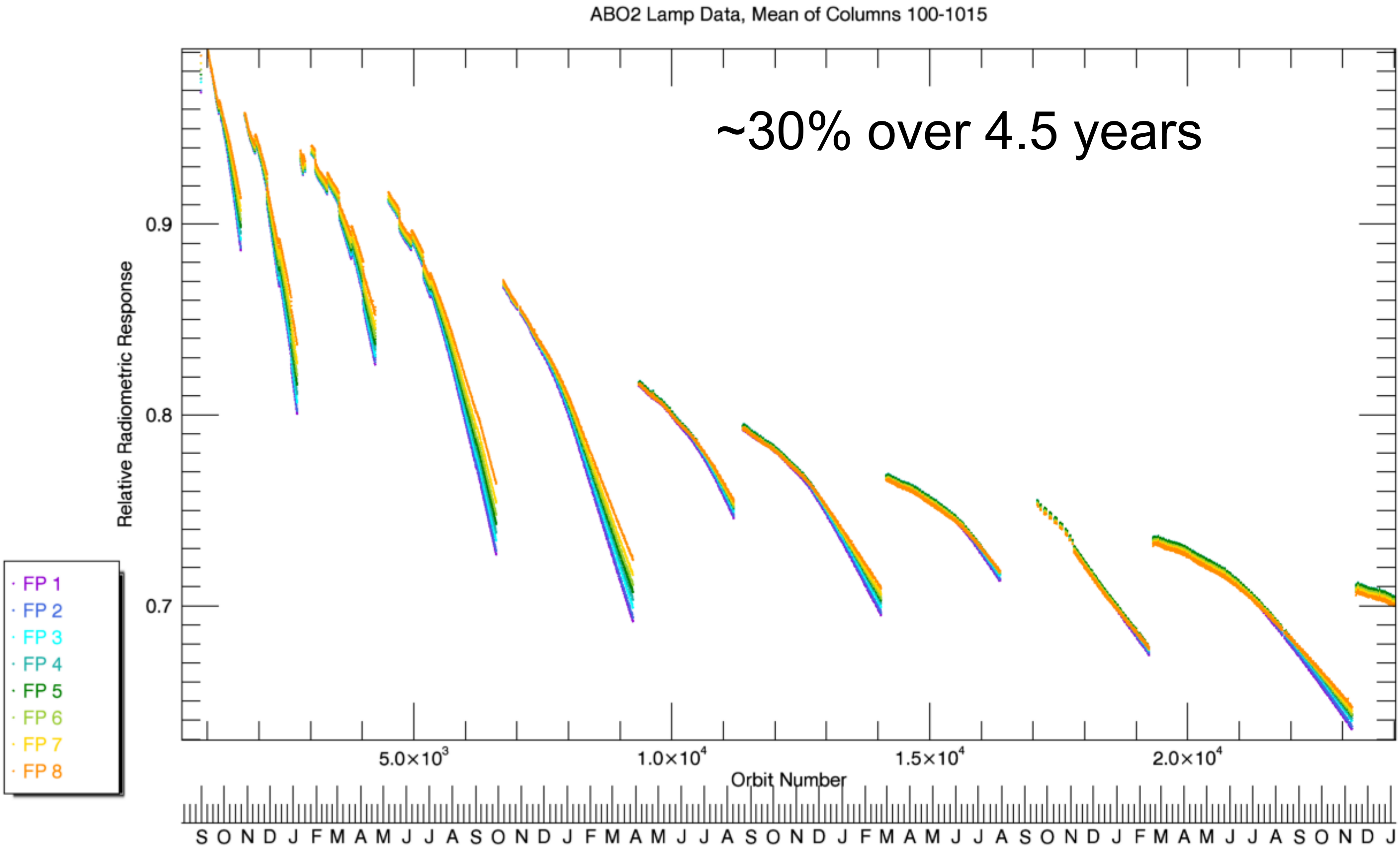


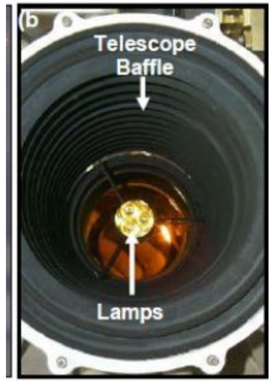


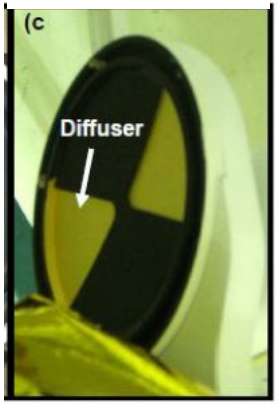


- Observations of diffuse radiation from the on-board incandescent lamps are used to trend the sample-to-sample gain differences and their changes over time.

Long-term Degradation of the Lamps and Their Diffuser





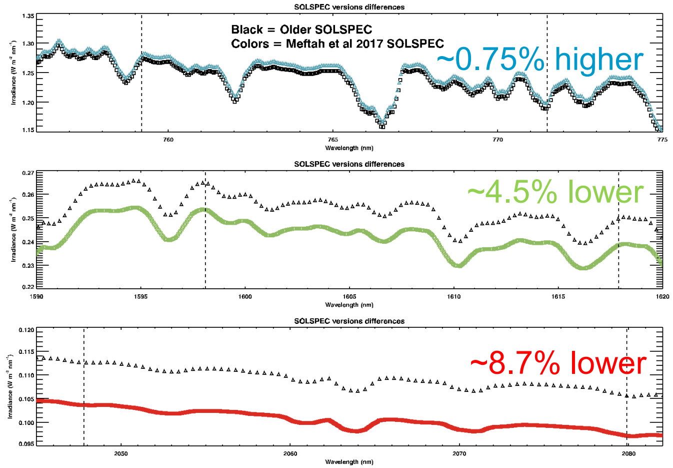


The OCO-2 instrument uses 3 lamps to illuminate a diffuser for tracking pixel-to-pixel gain variations. Lamp 1 is used on every orbit, and is cross-checked against lamps 2 and 3. All 3 lamps are still working, but the lamp diffuser has degraded more rapidly than the solar diffuser. Its rate of degradation is decreasing over time.

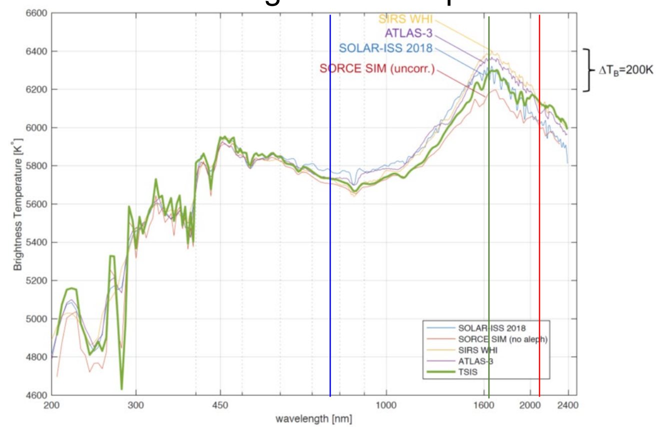
Updates to the Top of Atmosphere Solar Flux

- Accurate estimates of the top-of-atmosphere (TOA) solar flux are critical to X_{CO2} retrievals
- For OCO-2, we construct the solar spectrum by combining a high resolution solar “transmission spectrum” (provided by Geoff Toon) and a continuum derived from the ATLAS 3 SOLSPEC experiment
- Two recent studies have identified biases in the ATLAS 3 SOLSPEC fluxes
    - Reanalysis of the ISS SOLar SOLSPEC observations (Meftah et al. 2018)
    - New data from the ISS TSIS SSI instrument (Richard et al. 2018)
- Both studies show the largest differences in the CO_2 channels

Solar ISS values are:



TSIS-SIM Brightness Temperatures

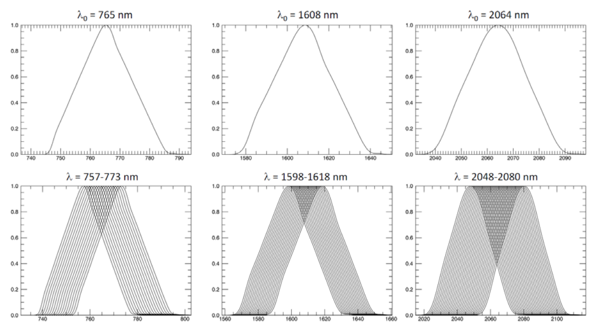


Largest Differences seen in the SWIR

Adjusting the OCO-2 Solar Continuum

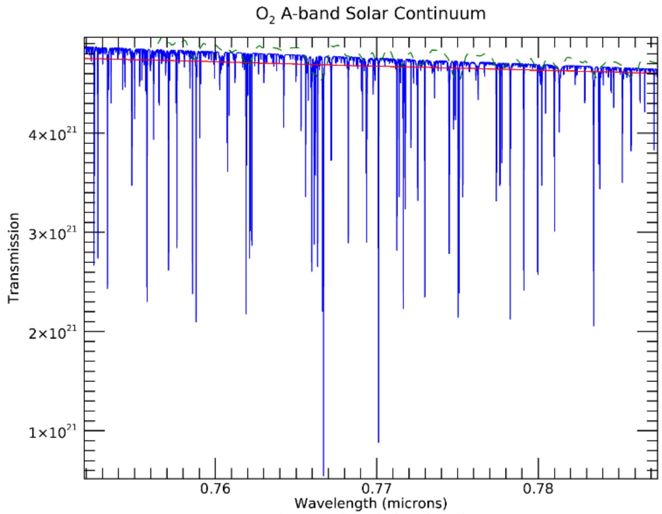
Approach:

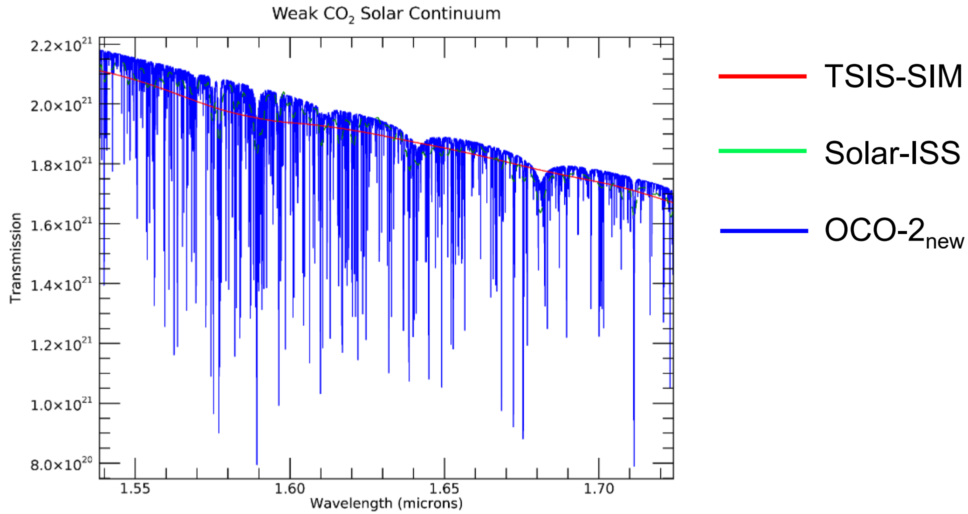
- Current OCO-2 solar spectral continuum in each channel (v6/v7/v8) was compared to the Solar-ISS solar spectra recently received from Meftah et al. and the TSIS-SIM solar spectra from Richard et al.
  - The TSIS-SIM values were adopted as the standard here
- The OCO-2 continuum values were:
  - Scaled by a multiplicative offset and slope (offset + slope*(λ-λ_{min})),
  - Multiplied by the high resolution transmission spectrum
  - Convolved with the TSIS-SIM Spectral Response Function (SRF)
- Plotting convention in plots that follow:
  - Original OCO-2 L2 continuum plotted in grey,
  - Scaled continuum plotted in black
  - TSIS-SIM plotted in red
  - Solar-ISS plotted in green
  - High-res OCO-2 solar spectra (blue)

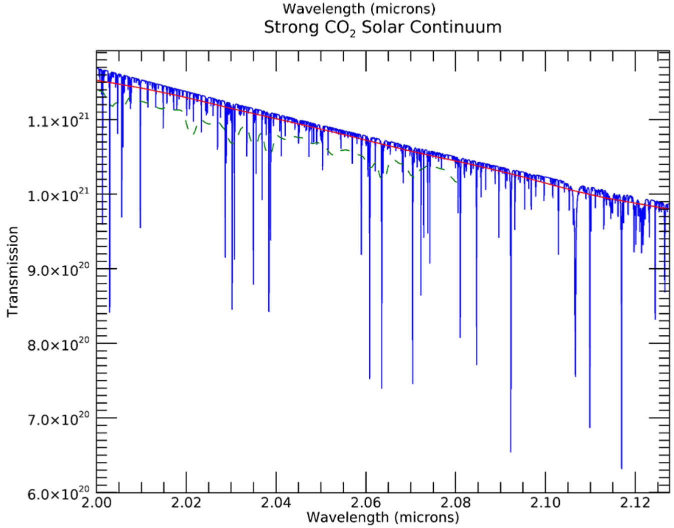


TSIS-SIM SRF

Solar Spectral Databases

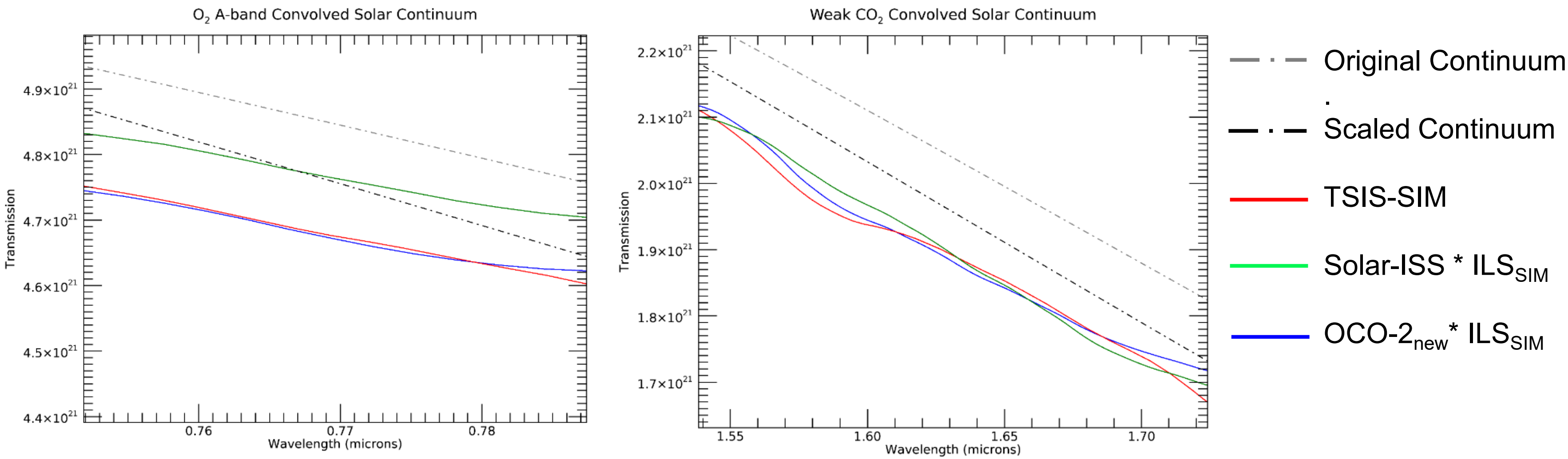


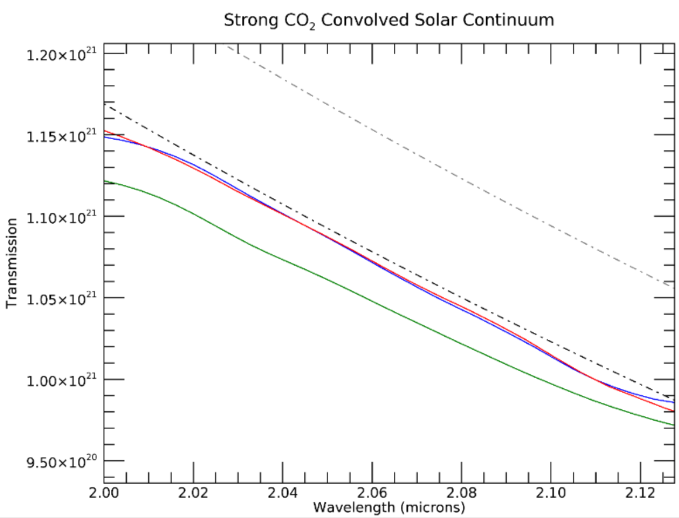




The OCO-2 continuum was scaled and then multiplied by the high-resolution solar line spectrum to produce a high resolution solar spectrum (blue). This spectrum is compared to the TSIS-SIM (red) and Solar-ISS spectrum (green) in each channel. The ABO2 and WCO2 channels have far more strong solar lines than the SCO2 channel.

Spectrally-Convolved Results





The OCO-2 high resolution solar spectrum with the scaled continuum was convolved with the TSIS-SIM spectral response function (SRF, blue) and compared to the TSIS-SIM (red) and the Solar-ISS spectrum (also convolved with the TSIS-SIM SRF (green)) to validate the scaled values.

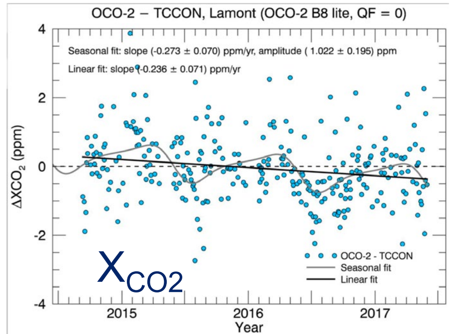
Summary of Solar Flux Results

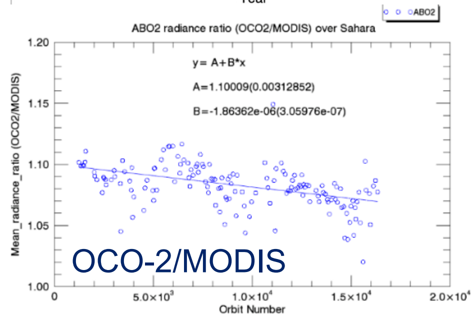
OCO-2 Continuum Scaling Factors:

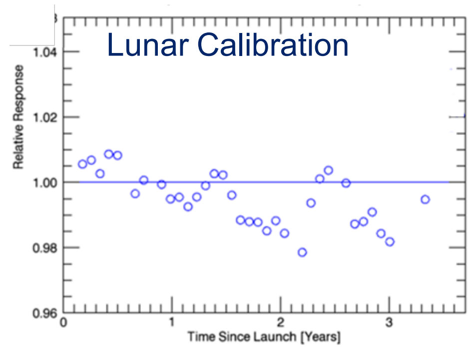
- ABO2 Scaling:
  - $(0.987 - 0.3\ \Delta\lambda) \times F_{c(old)}$, $\Delta\lambda = (\lambda - \lambda_{min})$, λ_{min} = 0.751880 µm
- WCO2 Scaling:
  - $(0.97 - 0.11\ \Delta\lambda) \times F_{c(old)}$, $\Delta\lambda = (\lambda - \lambda_{min})$, λ_{min} = 0. 1.53846 µm
- SCO2 Scaling:
  - $0.935 \times F_{c(old)}$, No slope correction needed
- With these scaling factors, the OCO-2 solar spectrum produces better fits the TSIS-SIM spectrum
- These tests also revealed systematic differences between the TSIS-SIM and Solar-ISS standards:
  - Solar-ISS results are ~1.6% higher than TSIS-SIM at 0.765 µm
  - Solar-ISS and TSIS-SIM results are comparable at 1.61 µm
  - Solar-ISS results are 2.5% lower than the TSIS-SIM near 2.06 µm

Known Issues: Long Term Radiometric Drifts

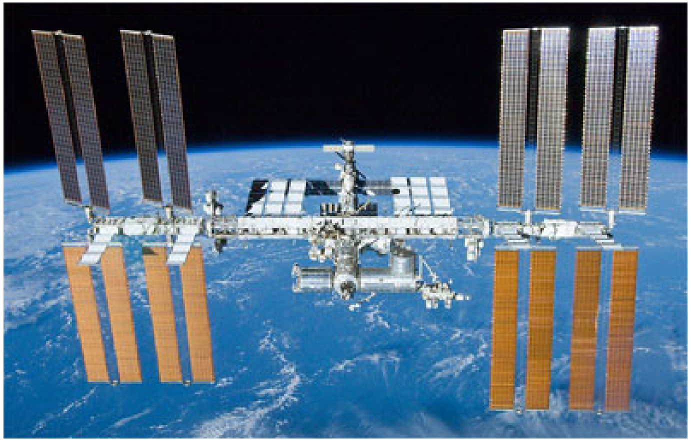
- Comparisons of the OCO-2 V8 product with TCCON indicate a long-term drift (0.1 ppm/yr)
- This drift is correlated with a long term drift in the radiometric calibration of the V8 L1b product
  - OCO-2 was cross calibrated against MODIS Aqua over the Sahara
  - Location box: 15°-23°N, 5°-17.5°E
  - Differences in viewing geometry (BRDF) and spectral interpolation may account for overall biases (based on RRV experience)
- Comparisons indicate ABO2 (O2 A-band) channel has a drift of -0.9% / year
- Similar drifts seen in lunar calibration trends
- These changes will addressed in the next data product.

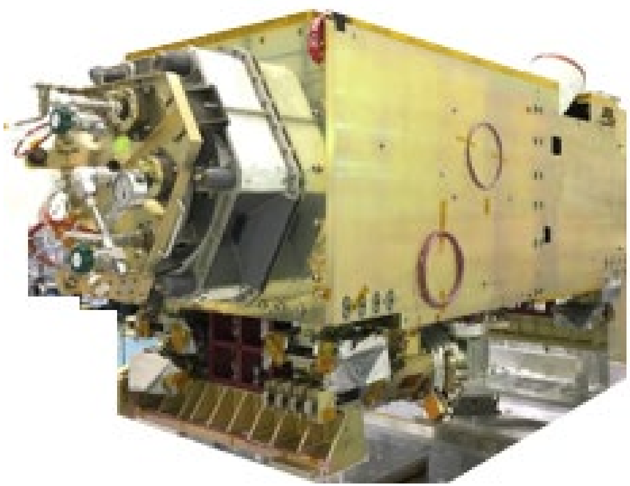






ISS OCO-3





- Scheduled for launch to the International Space Station (ISS) on or after 25 April 2019
- OCO-3 combines the OCO spectrometers with an agile, 2-axis pointing system
  - Facilitates observations of the ocean glint spot and validation targets.
  - Also has a snapshot mapping mode to collect dense datasets over 100km by 100km areas.

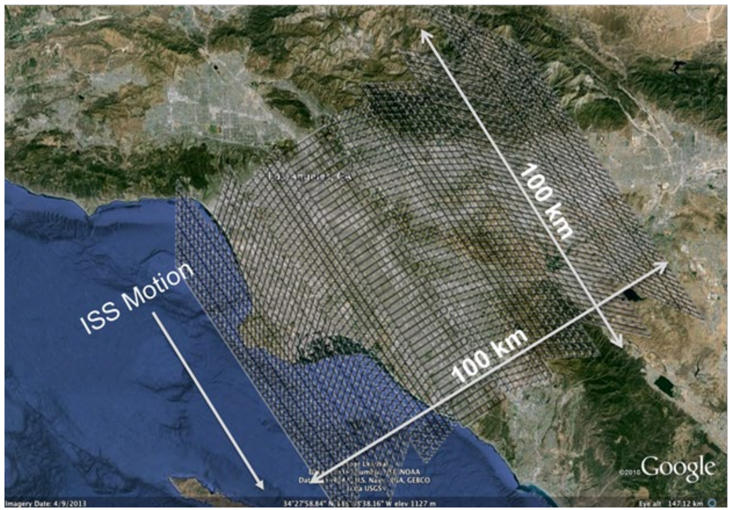
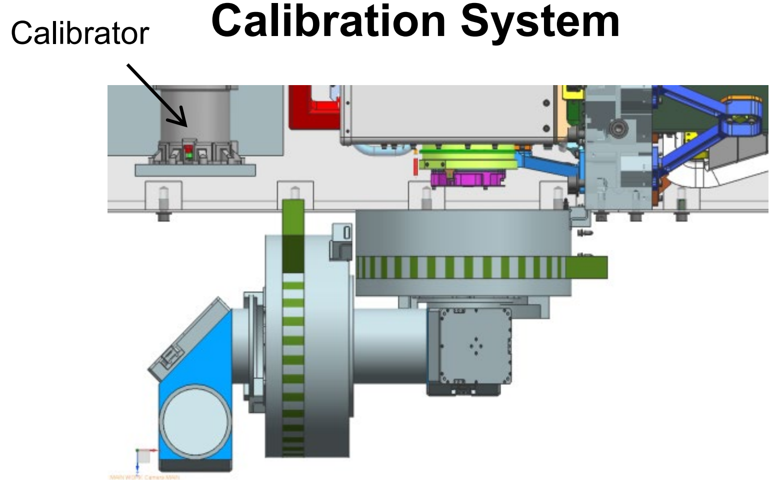


Figure 2: *Google map of the Los Angeles basin showing the coverage provided by the OCO-3 snapshot mapping mode. This mode can be used to map up to 100 targets each day.*

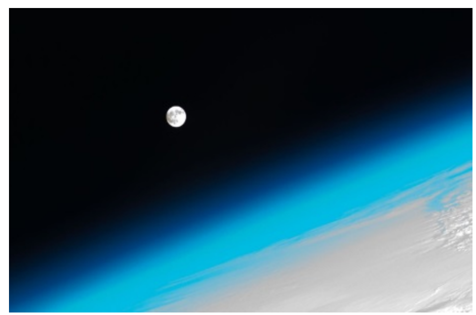
OCO-3 Calibration

- OCO-3 includes on-board calibration system to collect dark and lamp calibration observations
- Lunar, and vicarious calibration targets are also used for radiometric calibration
- Unlike OCO-2, OCO-3 cannot view the sun for solar calibration, so Lunar, lamp and vicarious calibration more important
- Lunar observations will also be used for geometric calibration
- Context cameras provide continuous opportunities for verifying the geometric calibration using land surface targets

Calibration System

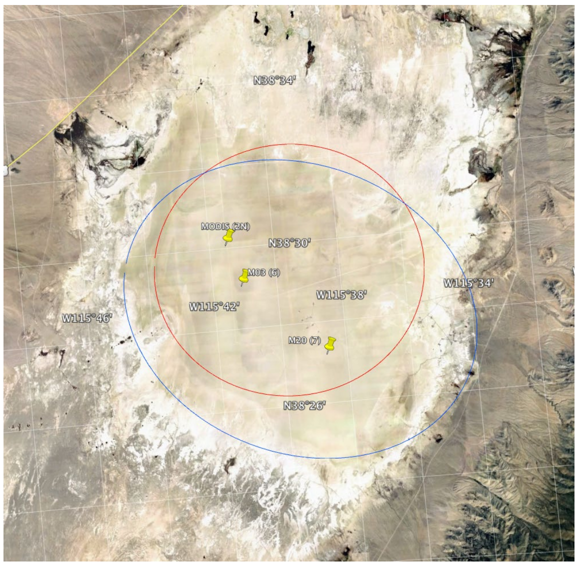


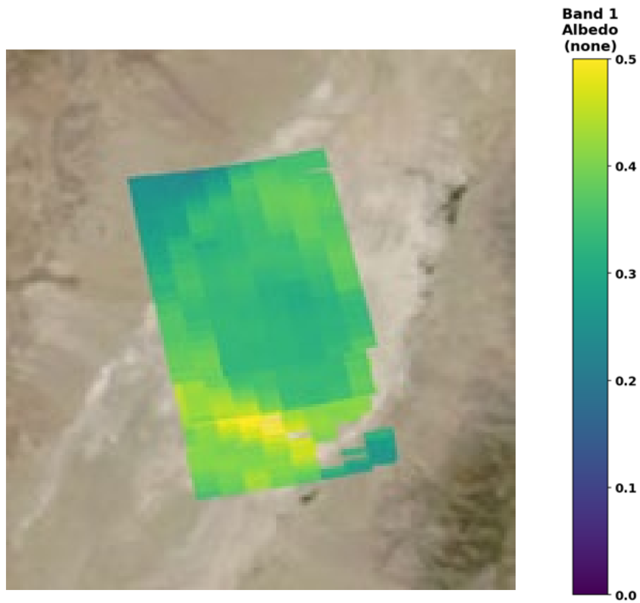
Lunar view from ISS



Vicarious Calibration – Railroad Valley (RRV)

- The Railroad Valley playa is a critical surface calibration site for several operating and planned Earth Science missions by NASA and its partners.
- RRV is the only instrumented site within the U.S. that is sufficiently homogeneous and undisturbed over a large enough area to enable vicarious calibration of large-footprint instruments, such as GOSAT, OCO-2, TanSat, GOSAT-2, OCO-3, and GeoCarb.

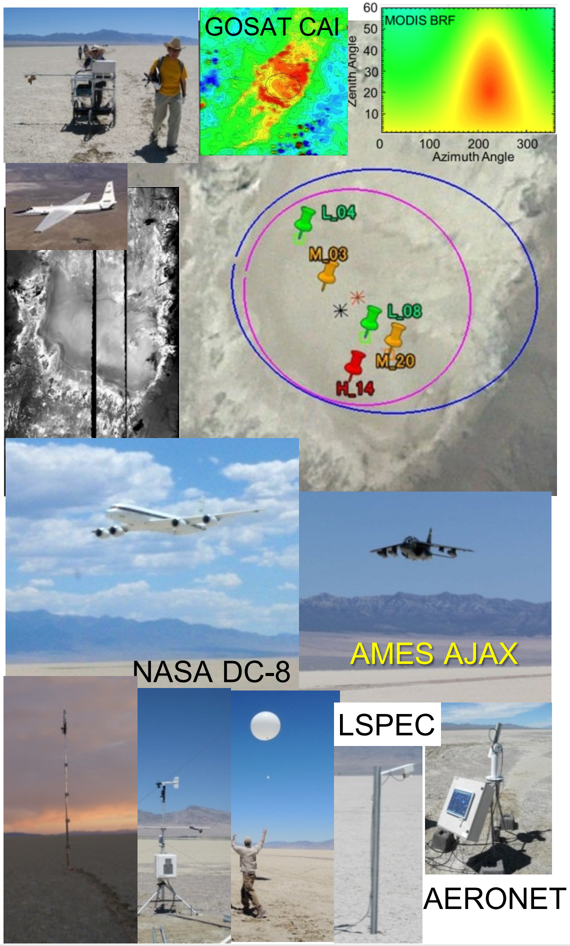




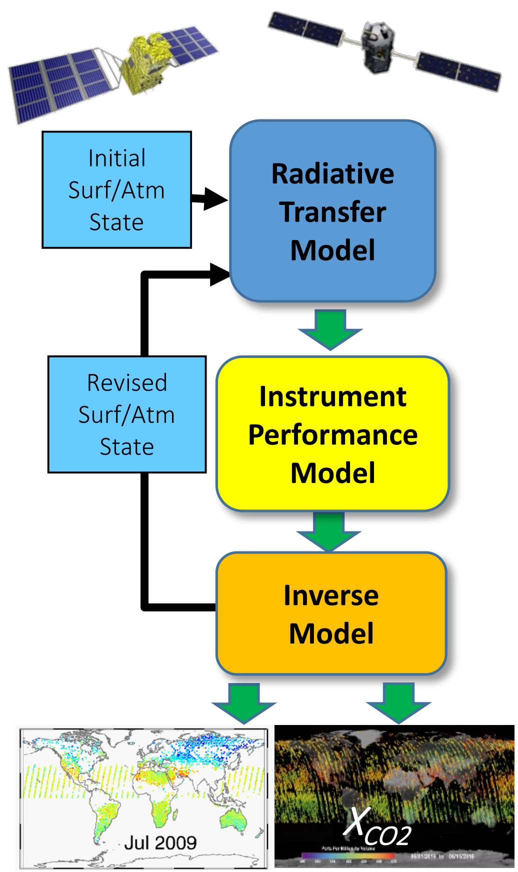
RRV shown with GOSAT footprints (left, ellipses) and OCO-2 target observations (right). Both missions require the whole playa.

the OCO/GOSAT Collaboration

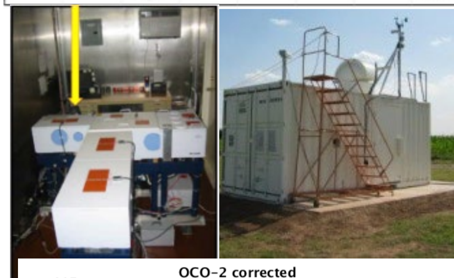
Vicarious Calibration

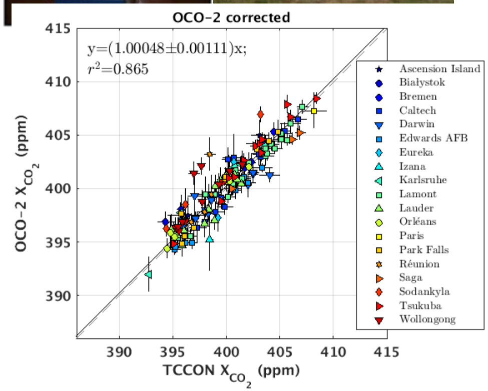


Retrieval Algorithm



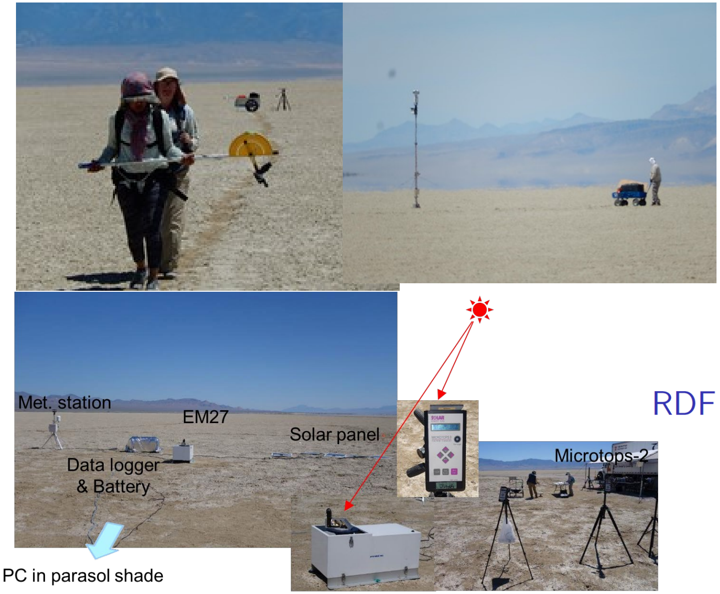
Validation

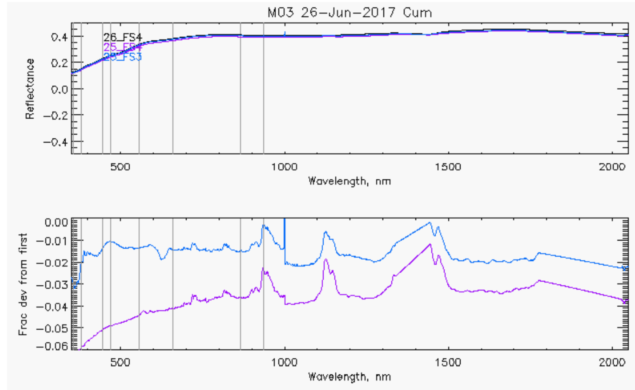




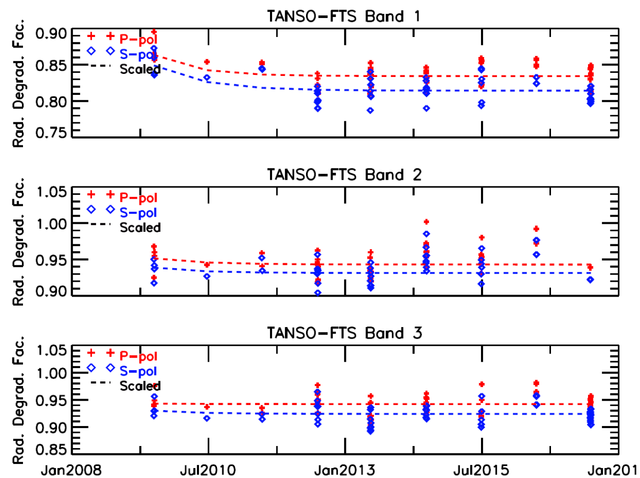
Annual Railroad Valley Campaigns

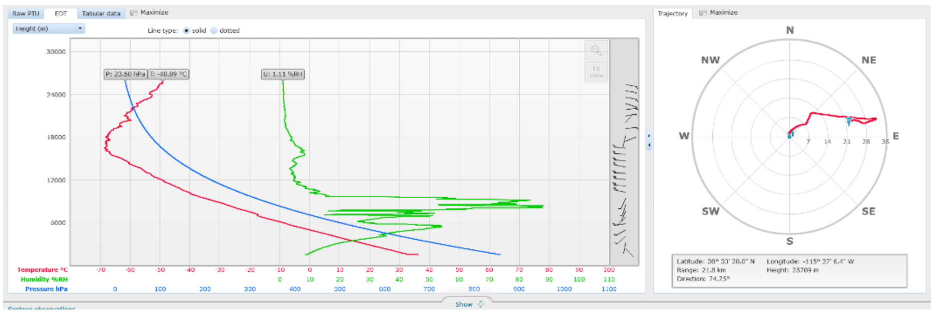
RRV_20:53:59(L1B)
GOSATTFTS201706232053036
0242_1BSPOD201202.01 05
RRV_20:54:02(CAM)





RDF versus preflight calibration

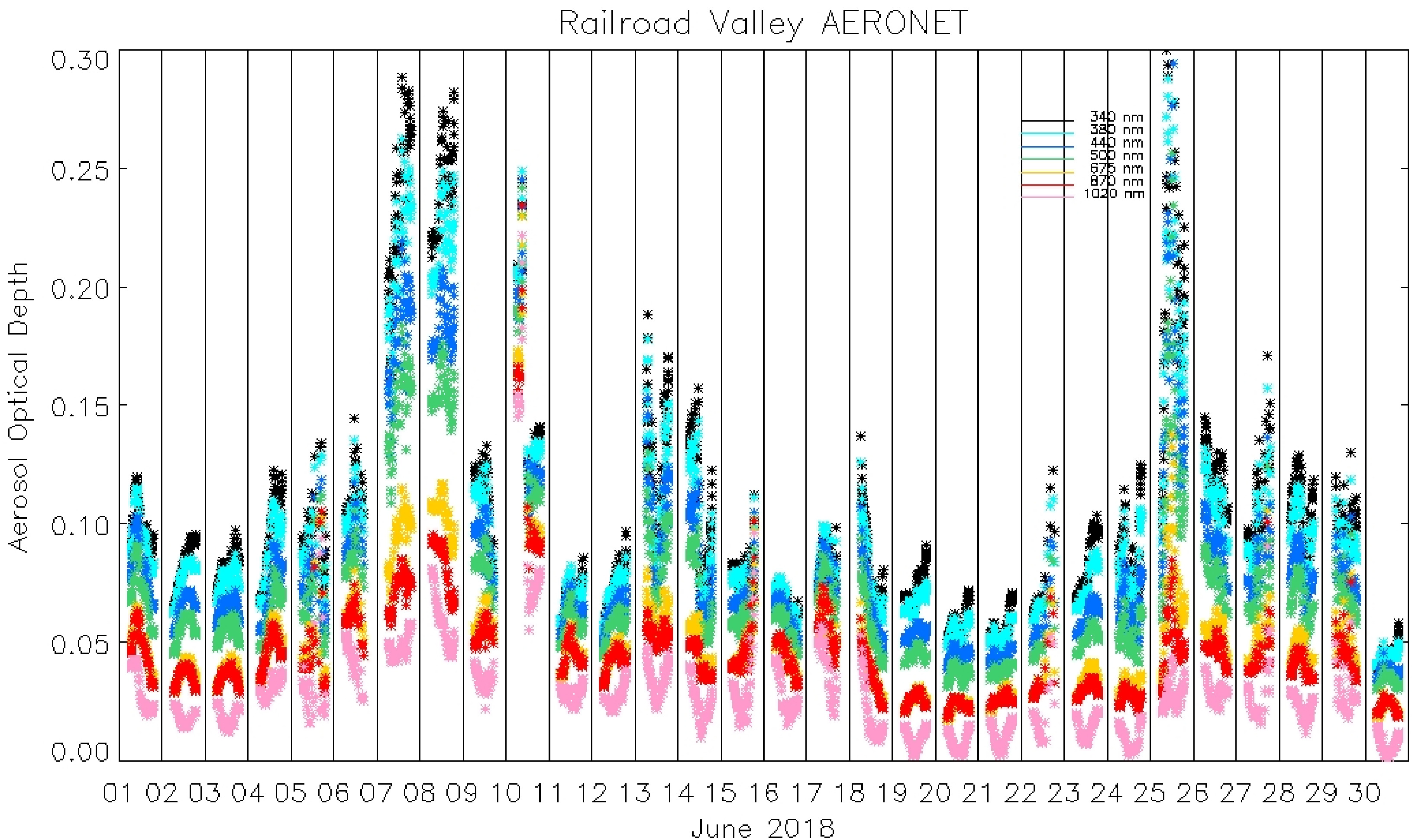




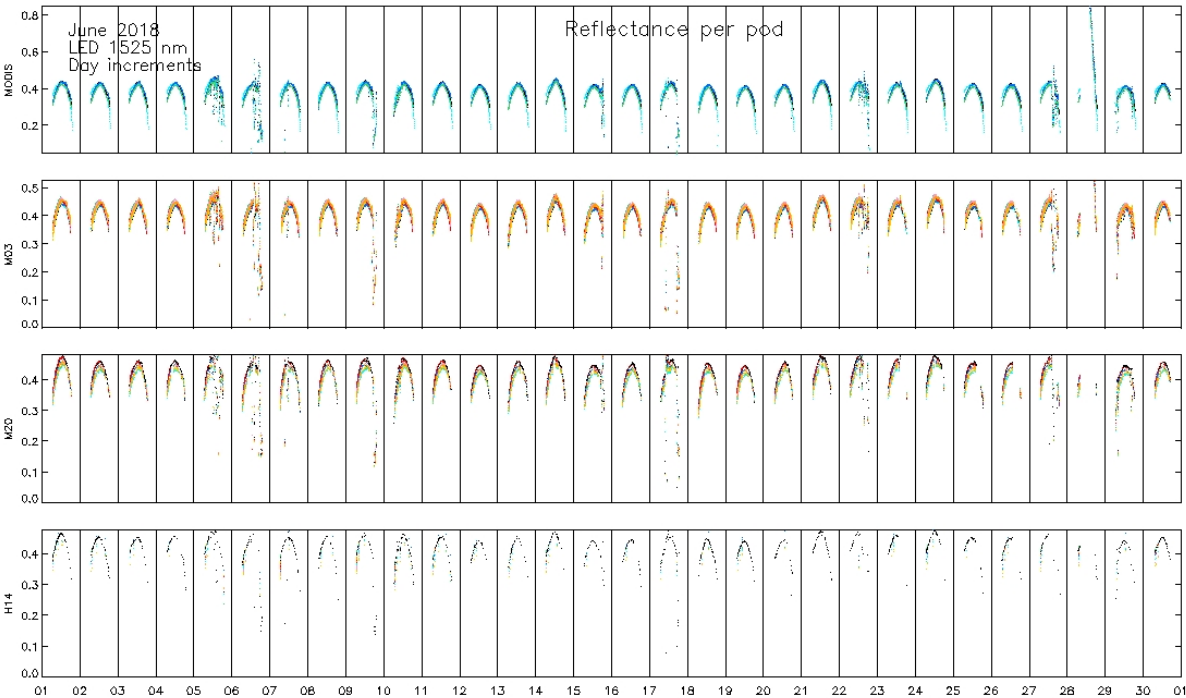
Annual campaigns characterize both surface and atmospheric properties.

[Kuze et al.]

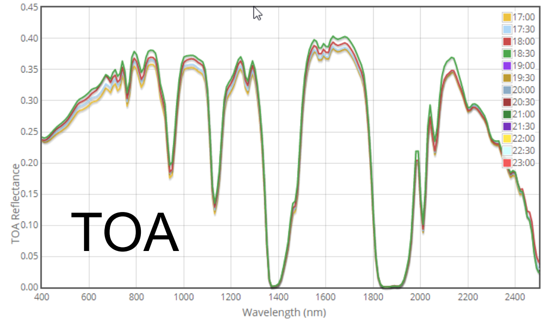
AERONET - Daily Aerosols Tracking over RRV

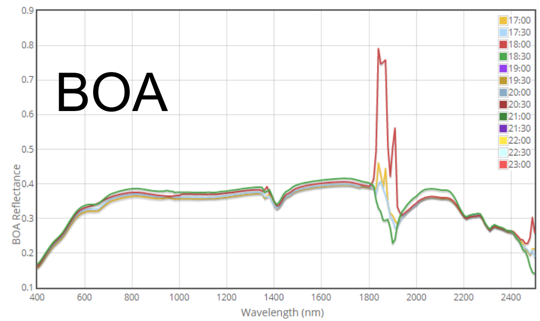


LSPEC – Daily Surface Reflectance Trending



June 2018

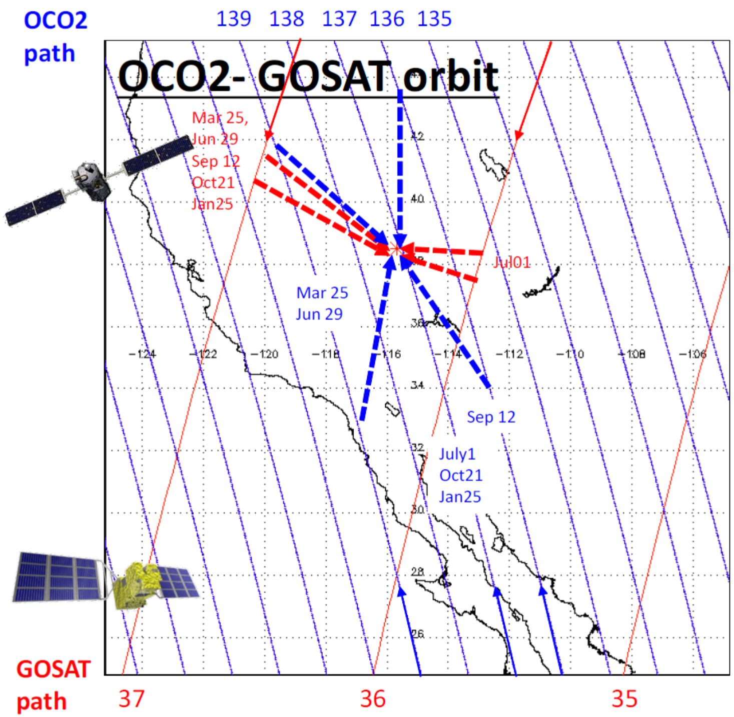




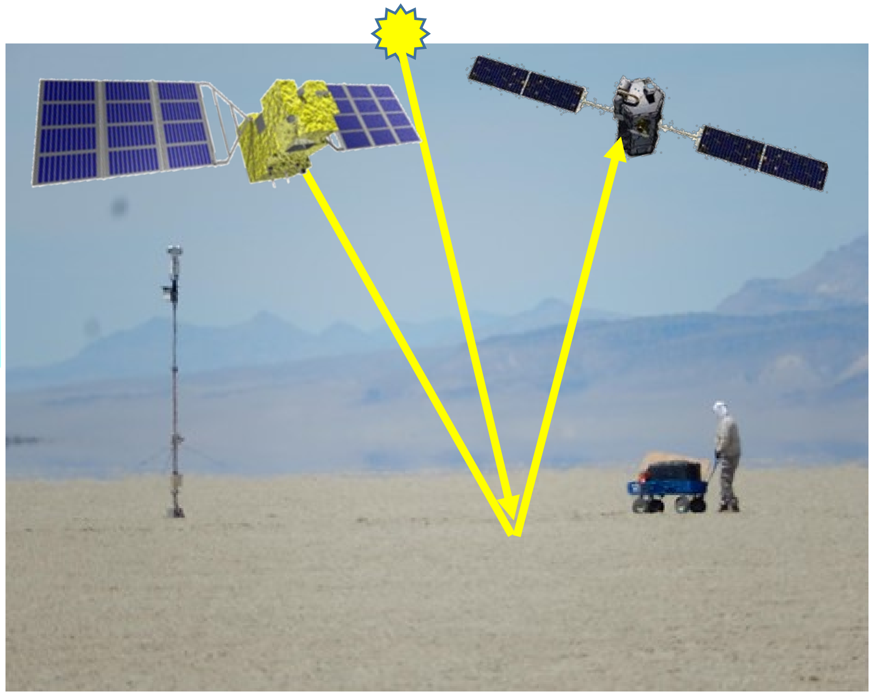
The autonomous LSPEC network (above) and RadCalNet (right) monitors daily reflectance variations.

RadCalNet sensors monitor spectra at surface (BOA) and estimate TOA reflectance.

Observing RRV from GOSAT and OCO-2



GOSAT targets the RRV playa from ground tracks shown in red while OCO-2 targets the playa from ground tracks are shown in blue. (Kataoka et al. AGU 2018)

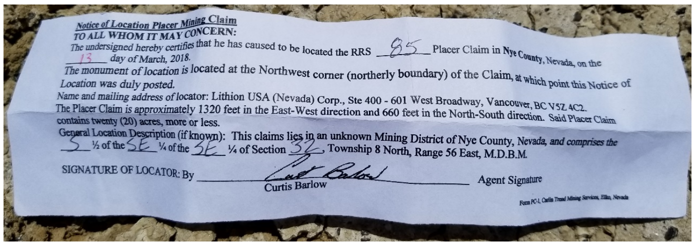


Because GOSAT and OCO-2 observe the RRV playa from different observing angles, the surface BRDF must be accurately known to cross calibrate the products. PARABOLA (tower at left) monitors BRDF on playa.

Threats to RRV by Lithium Mining Interests

- Recent mining claims threaten to disrupt the surface of the Railroad Valley playa, rendering it useless for vicarious calibration

Areas of the RRV playa that have been claimed by mining interests are shown in yellow and pink.



Notice of Location Placer Mining Claim

TO ALL WHOM IT MAY CONCERN:

The undersigned hereby certifies that he has caused to be located the RRS _85_ Placer Claim in Nye County, Nevada, on the _13_ day of March, 2018.

The monument of location is located at the Northwest corner (northerly boundary) of the Claim, at which point this Notice of *Location was duly posted.*

Name and mailing address of locator: Lithion USA (Nevada) Corp., Ste 400 - 601 West Broadway, Vancouver, BC V5Z 4C2.

The Placer Claim *is approximately* 1320 feet in the East-West direction and 660 feet in the North-South direction. Said Placer Claim contains twenty (20) acres, more or less.

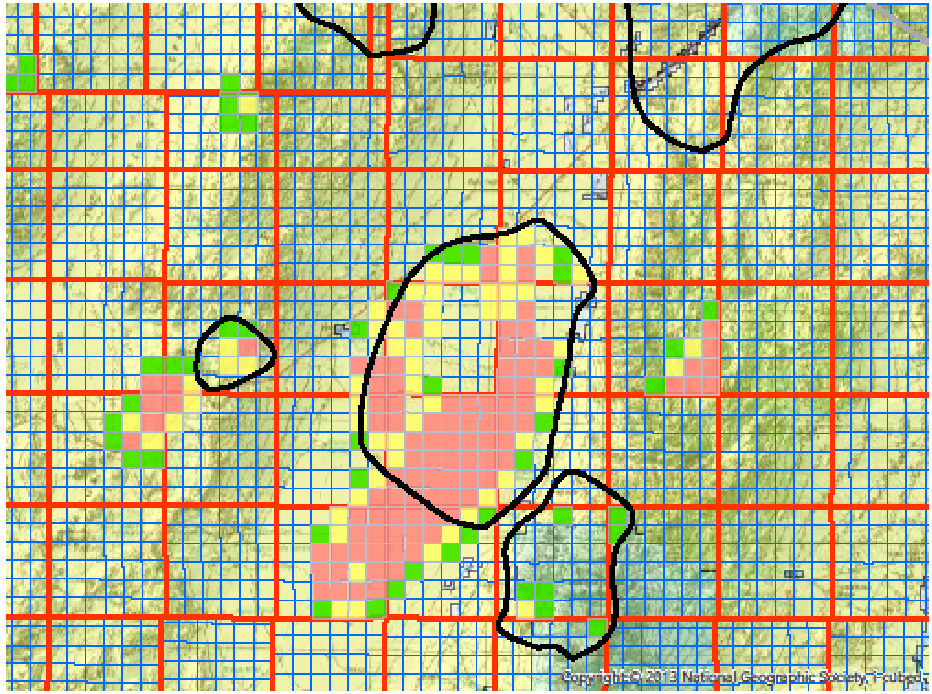
General Location Description (if known): This claims lies in an unknown Mining District of Nye County, Nevada, *and comprises the* _S_ ½ of the _SE_ ¼ of the _SE_ ¼ of Section _32_, Township 8 North, Range 56 East, M.D.B.M.

SIGNATURE OF LOCATOR: By __________ Agent Signature

Curtis Barlow

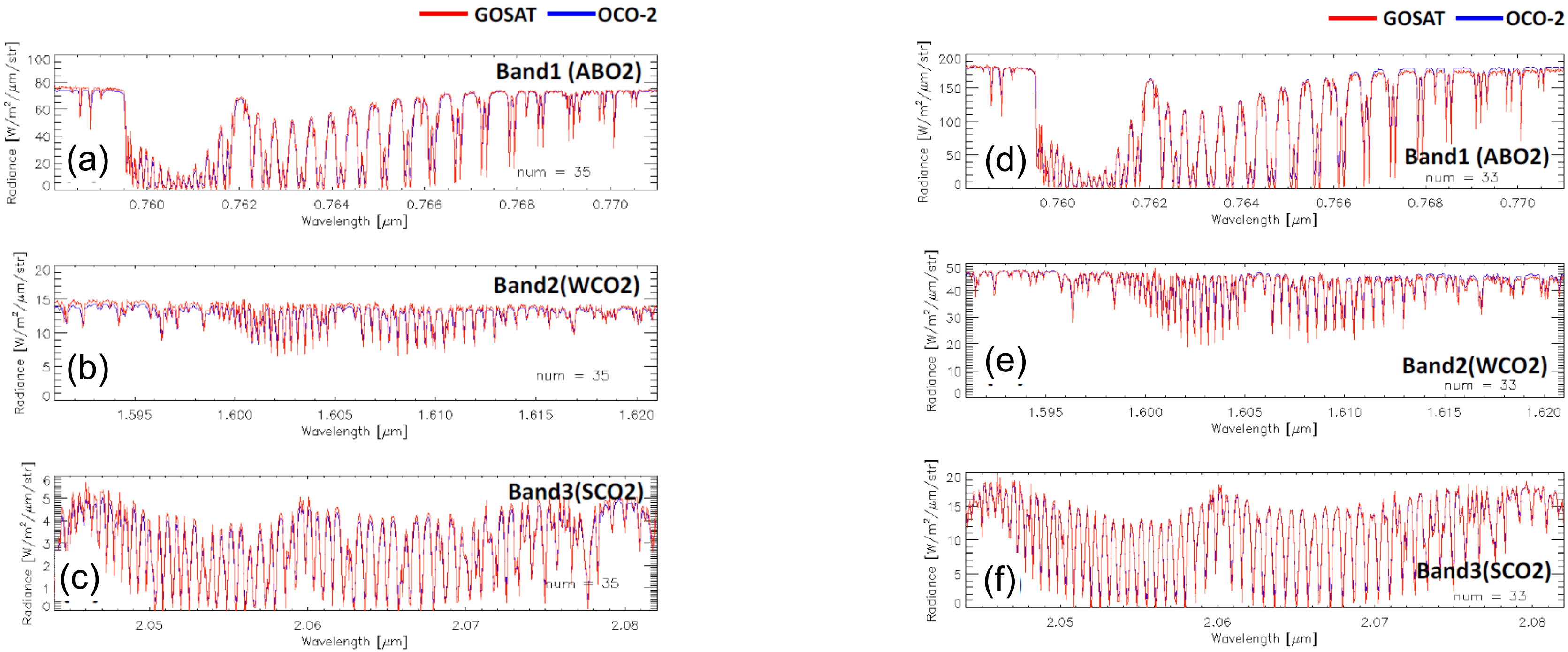
Form PC-1, Carlin Trend Mining Services, Elko, Nevada

Example of a “Pacer Claim” found on RRV in Summer 2018



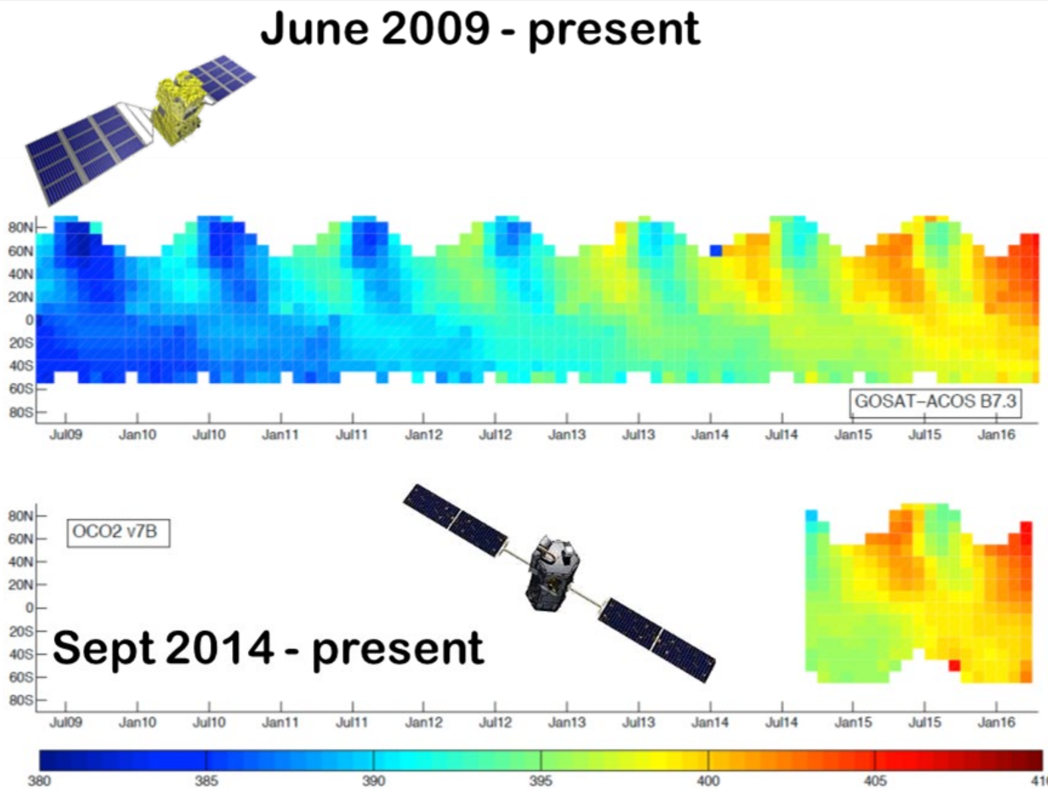
- NASA Science Directorate developed a “Withdrawal Application” to be submitted to the U.S. Bureau of Land Management to restrict public uses of the RRV playa that disturb the surface

Cross-Calibration of GOSAT and OCO-2 over the Pseudo Invariant Calibration Sites (PICS)



Coincident spectra of the (a) O_2 A-band, (b) 1.61 μm CO_2 band and (c) 2.06 μm CO_2 bands from GOSAT TANSO FTS (red) and OCO-2 (blue) collected over a cloud-free scene over the Pacific Ocean. (credit: Kataoka et al., 2017). Coincident spectra of the (d) O_2 A-band, (e) 1.61 μm CO_2 band and (f) 2.06 μm CO_2 bands from GOSAT TANSO FTS (red) and OCO-2 (blue) collected over the Sahara Desert. (Kataoka et al. 2017)

Creating Harmonized Products



The GOSAT and OCO-2 measurements were cross-calibrated, and their data products were cross-validated to produce a continuous, harmonized data record that spanned the lifetimes of both missions.

Summary

- Space-based remote sensing observations hold substantial promise for verifying inventories and monitoring changes in the natural carbon cycle associated with climate change
  - These data complement existing ground-based and aircraft based in situ data with increased coverage and sampling density
- Over the next decade, a succession of missions with a range of CO_2 and CH_4 measurement capabilities will be deployed
  - These missions are demonstrating the precision and resolution needed to monitor inventories, but improvement in accuracy and coverage needed to for this application
  - Much greater benefits could be achieved if these sensors can be cross-calibrated and their products can be cross-validated so that they can be combined into a long, harmonized GHG data record
- Well coordinated constellations of GHG satellites, combined with improved ground and aircraft-based data and flux inversion modeling tools could meet the expanding needs for independent verification of GHG inventories